JOURNAL OF MATERIALS SCIENCE 30 (1995) 5173–5177

Stress dependence of bistability in a zero-magnetostrictive amorphous wire

J. GONZÁLEZ, K. KUŁAKOWSKI*, P. ARAGONESES, J. M. BLANCO, E. IRURIETA
Departamento de Fisica de Materiales, Facultad de Ciencias Quimicas, Universidad del Pais Vasco, 20080 San Sebastian, Spain

New data on the bistability of $(Co_{95}Fe_5)_{72.5}Si_{12.5}B_{15}$ amorphous wire are discussed in the framework of a simple model of magnetic interaction between inner core and outer shell of a wire. Experimental results are reported on the tensile stress and annealing-time dependence of switching field and remanence magnetization, for longitudinal and circular hysteresis loops. Theoretical considerations allow various scenarios of the bistability effect to be distinguished, which are helpful in our understanding of the experimental data.

1. Introduction

Large Barkhausen jumps in amorphous magnetostrictive wires are known to be present in both iron-rich [1] and cobalt-rich [2] wires, where magnetostriction is of a different sign. The effect leads to magnetic bistability and is important for technological applications [2]. Nearly zero-magnetostrictive amorphous alloys are of current interest [3], but the effect of bistability in such wires was observed recently for the first time [4] in as-quenched cobalt-based wire at low temperature. Alternatively, simultaneous action of tensile and torsional stress [4] or stress annealing [5] is necessary to achieve bistable behaviour at room temperature.

The bistability effect is known [2] to be closely related to internal stresses and their influence on domain structure. Although it is particularly difficult to evaluate this influence in zero-magnetostrictive samples, it seems to be possible [6] that bamboo-like domains are present here, as in the case of negative magnetostriction cobalt-based wires [2].

In the present work, we report the results of our experimental investigations on bistability in nearly zero-magnetostrictive cobalt-based wire at room temperature. Switching field and remanence magnetization dependences on applied stress are obtained for various times of stress annealing. As reported elsewhere [4–6], no bistability could be observed in as-cast wire. However, for stress-annealed wires, we find that the bistability arises and vanishes, and it is shown below that this behaviour distinctly depends on the applied tensile stress and annealing time.

To interpret these experimental results, we analyse the role of ferromagnetic interaction between inner core (IC) and outer shell (OS) of the wire. Special attention is given to the magnetic state of the interface which mediates between IC and OS. Helical magnetic anisotropy is expected in this interface [7]. Below we develop a simple model of three interacting areas; IC, OS and the interface, which will be termed HI (helical interface). This model description allows the necessary conditions of the existence of the bistability effect to be formulated separately for longitudinal and circular hysteresis loops. According to these conditions, the bistability itself is unstable with respect to changes of the magnetic state of a wire, including, in particular, the state of its helical interface.

2. Experimental procedure

The metallic glass was supplied by Unitika Ltd Co. (Japan). The nominal composition of the wire is $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$, and its dimensions are 0.12 mm diameter and 10 cm length. Hysteresis loops M_z–H_z and M_z–H_ϕ have been obtained by the conventional induction method at a frequency of 50 Hz. Here, M_z is the longitudinal (parallel to the wire) component of magnetization, H_z and H_ϕ are the longitudinal and azimuthal magnetic fields. H_ϕ is created by the electric current flowing along the wire and it is known to be proportional to the distance from the wire axis. This current is less than 20 mA, which is not strong enough to heat a wire. Electric current was also applied to anneal the wire; its value was 380 mA, which corresponds to a perpendicular magnetic field of 800 A m^{-1} on average over the wire volume. The annealing stress was 550 MPa. Measurements were performed on the wire at the same setting as for annealing, so some residual torsion was likely to occur. Experimental devices and other details of the measurements have been reported elsewhere [7, 8].

3. Results

First, we describe the results obtained for the longitudinal hysteresis loop (M_z–H_z). For the as-quenched

---

* *Permanent address*: Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, Cracow, Poland.

sample, no bistability is observed; we believe that for this case, an inner core still does not exist. The effect is absent also for very short annealing times, up to a given value of applied stress (300 MPa for $t_{\mathrm{ann}} = 1$ min). The applied stress dependences of the reduced remanence magnetization, $m_{\mathrm{r}}(\sigma)$, are shown in Fig. 1 for four values of the time of stress annealing: $t_{\mathrm{ann}} = 1$, 5, 60 and 360 min. For short annealing times, i.e. 1 and 5 min, we observe a maximum of m_{r} with applied stress. For $t_{\mathrm{ann}} = 60$ min and longer, this maximum is distinctly shifted towards larger values of applied stress, i.e. from 400 MPa for $t_{\mathrm{ann}} = 1$ min and 500–600 MPa for $t_{\mathrm{ann}} = 5$ min to 700–800 MPa. Also, the character of the $m_{\mathrm{r}}(\sigma)$ curve is changed: for the two longer values of t_{ann} the reduction of m_{r} after its maximum is much slower. The abrupt reduction of m_{r} leads to vanishing of bistability above 900 MPa; this is the case for $t_{\mathrm{ann}} = 1$ and 5 min.

The applied stress dependence of the switching field, H^* (σ), is shown in Fig. 2, for the same values of annealing time as above. For $t_{\mathrm{ann}} = 1$ min, the increase in the switching field with stress is very sharp and cannot be fitted with the square root of stress-induced anisotropy. This plot exhibits a characteristic shape, similar to that found for cobalt-based wire with negative magnetostriction. Such a shape was interpreted previously [9] as the fingerprint of the propagation mechanism in a wire with a very narrow inner core. In wires with negative magnetostriction, the radius of the inner core is further reduced by the applied stress. This mechanism could be active here for very short annealing times, where bistability exists but the magnetostriction is negative ($t_{\mathrm{ann}} = 1$ min). For longer annealing times, the magnetostriction is expected to become higher (its absolute value decreases), and the nucleation mechanism is activated. It is not clear from our data which mechanism is active for $t_{\mathrm{ann}} = 5$ min. It seems that for $t_{\mathrm{ann}} = 60$ min the plot of the switching field versus applied stress could be fitted by the square root of stress. This well-known dependence is abruptly changed near $\sigma = 500$ MPa. The switching field is switched itself from about 33 A m^{-1} below 500 MPa to 5–10 A m^{-1} above 500 MPa. Even for $t_{\mathrm{ann}} = 5$ min we have two experimental points which show a similar abrupt reduction of the switching field (see Fig. 2).

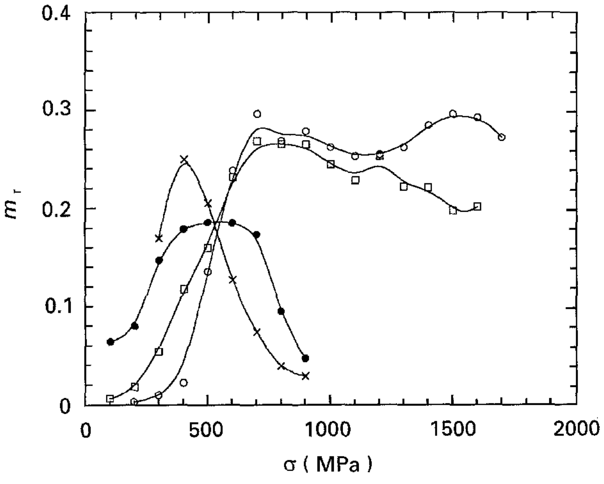

Figure 1 Reduced remanence magnetization for the M_z–H_z hysteresis loop for different annealing times: (×) 1 min, (●) 5 min, (□) 60 min, (○) 360 min.

The experimental data of m_{r} and H^* for the circular hysteresis loop (M_z–H_Φ) are shown in Figs 3 and 4, respectively. The plots are given against applied stress for the same values of annealing time, i.e. 1, 5, 60 and 360 min. For $t_{\mathrm{ann}} = 1$ min, the bistability effect vanishes up to an applied stress equal to 500 MPa, and above 1000 MPa. For subsequent values of t_{ann}, bistability vanishes above 900, 1600 and 800 MPa, respectively. This vanishing cannot be correlated with the annealing time, but rather with small values of the remanence magnetization, if any correlation can be found. For three values of t_{ann} we observe a maximum of m_{r} near, say, $\sigma = 700$ MPa. This maximum is very sharp for $t_{\mathrm{ann}} = 60$ and 360 min. For the case of $t_{\mathrm{ann}} = 1$ min, only the decreasing part of the plot of $m_{\mathrm{r}}(\sigma)$ is visible.

The stress dependences of the switching field for the M_z–H_Φ hysteresis loop are rather smooth for short annealing times ($t_{\mathrm{ann}} = 1$ and 5 min), and they show a reduction from higher values (25 and 33 A m^{-1}) to

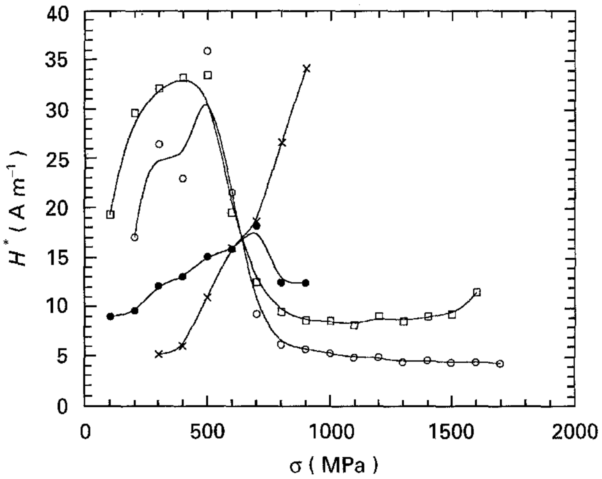

Figure 2 Switching field for the M_z–H_z hysteresis loop for different annealing times. For key, see Fig. 1.

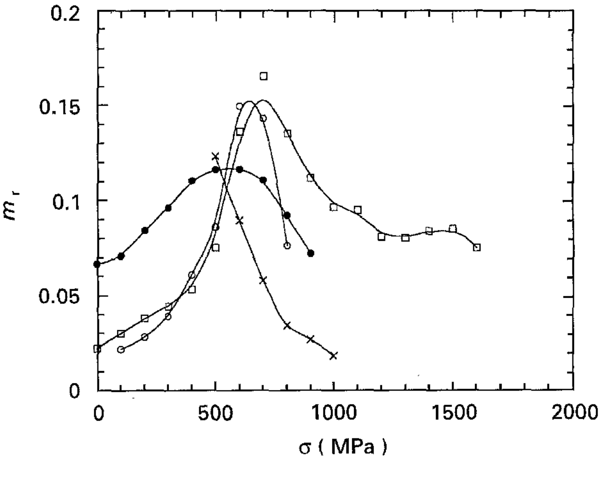

Figure 3 Reduced remanence magnetization for the M_z–H_Φ hysteresis loop for different annealing times. For key, see Fig. 1.

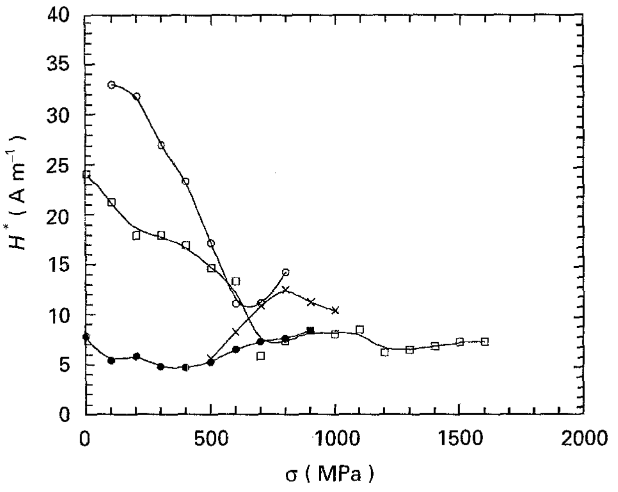

Figure 4 Switching field for the M_z–H_ϕ hysteresis loop for different annealing times. For key, see Fig. 1.

lower ones (14 and 7 $\mathrm{A\,m^{-1}}$) for $t_{\mathrm{ann}} = 60$ and 360 min, respectively (see Fig. 4).

4. Formulation of the model

In magnetostrictive wires, applied tensile stress strongly influences the domain structure. If $\lambda > 0$ (iron-rich alloys), the inner core increases with stress [10] and finally it occupies the whole volume of a wire. If $\lambda < 0$ (cobalt alloys), the outer shell dominates [9, 11]. On the contrary, for nearly zero-magnetostrictive wire, both inner core and outer shell coexist and interact in the whole range of applied stress. In this section an attempt is presented to describe the possible consequences of this interaction. The initial picture is based on the paper of Vazquez *et al.* [7]

Let us treat the whole magnetization of the inner core as one magnetic moment, m_{IC}. This moment is directed along the wire. Another magnetic moment, m_{OS}, is assigned to the outer shell. Originating from the bamboo-like domain structure, the orientation of this moment is circular and it is perpendicular to the wire axis. The orientation of local magnetic moments, when passing along a wire radius, changes from one parallel to the wire axis (near to the centre) to one perpendicular (near to the surface).

In a zero-magnetostrictive wire, local magnetoelastic anisotropy is weak. As the thickness of the domain wall scales with $K^{-1/2}$ [12], where K is an anisotropy energy, we expect this thickness to be not less than 1 μm. The orientation of local magnetic moments within this interface is close to the helical one. We intend to assign a third magnetic moment, m_{HI}, to the interface. It is natural to expect that this moment interacts directly with m_{IC} and m_{OS}. Therefore, magnetic energy can be written as

$$E = -h\,(m_{\mathrm{IC}} + m_{\mathrm{OS}} + m_{\mathrm{HI}}) - J_1\, m_{\mathrm{IC}}\, m_{\mathrm{HI}} - J_2\, m_{\mathrm{HI}}\, m_{\mathrm{OS}} \tag{1}$$

where h is the magnetic field (comprising $g\mu_{\mathrm{B}}$) and Js are the mean ferromagnetic exchange integrals between the magnetic moments of particular parts of a wire. This simple notation allows us to distinguish some possible scenarios of the remagnetization of a wire. We assume that a given value of magnetic field, say h_{n}, is needed to reverse m_{IC} in the absence of exchange interaction. This field is supposed to be due to the usual nucleation mechanism, with one exception, which will be remarked later. The exchange interactions, J, however, modify the actual value of the switching field.

Let us start from the case of the longitudinal hysteresis loop, M_z–H_z, where an external magnetic field is applied along the wire axis. In the presence of an exchange, the switching field is altered by the mutual interaction of magnetic moments. This alteration depends on the actual orientation of the moments. We should distinguish the cases when m_{IC} or m_{HI} are reversed at first. For the former, a magnetic field is needed

$$h_z(\mathrm{IC}) = h_{\mathrm{n}} + J_1\, m_{\mathrm{HI}} \cos\theta \tag{2}$$

where an angle θ is between m_{IC} and m_{HI}. (The index z is introduced to distinguish between both kinds of hysteresis loops.) For the latter, the switching field is

$$h_z(\mathrm{HI}) = [J_1\, m_{\mathrm{IC}} \cos\theta + J_2\, m_{\mathrm{OS}} \sin\theta]\, f(\theta) \tag{3}$$

where $f(\theta)$ is a function which depends on the mechanism of remagnetization. For irreversible movement of domain walls, it is equal to $1/\cos\theta$ ([12], p.289). The actual value of the switching field is equal to $h_z(\mathrm{IC})$ if $h_z(\mathrm{IC}) < h_z(\mathrm{HI})$, and it is equal to $h_z(\mathrm{HI})$ in the opposite case.

The moment m_{OS} is reversed simultaneously with m_{HI}. Further evolution of the system still depends on some other conditions. In the former case, when the inner core is remagnetized as the first one, the effective magnetic field acting on the helical interface can still be too weak to reverse m_{HI} immediately. Then we observe two steps in the hysteresis loop, and the second value of the coercive field is equal to

$$h_z(\mathrm{HI/IC}) = [J_2\, m_{\mathrm{OS}} \sin\theta - J_1\, m_{\mathrm{IC}} \cos\theta]\, f(\theta) \tag{4}$$

(The above notation is introduced to mark the succession of reverses of magnetic moments: $h_z(\mathrm{HI/IC})$ is the switching field of m_{HI}, if m_{IC} has been reversed previously.) However, if $h_z(\mathrm{HI/IC}) < h_z(\mathrm{IC})$, all magnetic moments are reversed simultaneously at $h_z(\mathrm{IC})$. Note that the condition $h_z(\mathrm{IC}) < h_z(\mathrm{HI})$ is to be fulfilled for this scenario, as noted above.

The other subcase is when $h_z(\mathrm{HI}) < h_z(\mathrm{IC})$, m_{HI} is reversed, but still m_{IC} is not. This means, that $h_z(\mathrm{HI}) < h_z(\mathrm{IC/HI})$, where

$$h_z(\mathrm{IC/HI}) = h_{\mathrm{n}} - J_1\, m_{\mathrm{HI}} \cos\theta \tag{5}$$

Here again, all moments are reversed at the external field equal to $h_z(\mathrm{HI})$, if $h_z(\mathrm{IC/HI}) < h_z(\mathrm{HI})$.

Similar arguments may be presented for the circular hysteresis loop. Here, external magnetic field is supposed to be antiparallel to m_{OS}. At first, we must distinguish two cases: $h_\phi(\mathrm{OS}) < h_\phi(\mathrm{HI})$ and the opposite, where

$$h_\phi(\mathrm{OS}) = J_2\, m_{\mathrm{HI}} \sin\theta \tag{6}$$

$$h_\phi(\mathrm{HI}) = [J_1\, m_{\mathrm{IC}} \cos\theta + J_2\, m_{\mathrm{OS}} \sin\theta]\, f(\pi/2 - \theta). \tag{7}$$

In the former case the situation is as follows: either $h_\Phi(\mathrm{HI/OS}) < h_\Phi(\mathrm{OS})$, and then both m_{HI} and m_{OS} are remagnetized simultaneously, or $h_\Phi(\mathrm{HI/OS}) > h_\Phi(\mathrm{OS})$, then the second step of remagnetization is the reversion of m_{HI} at the field $h_\Phi(\mathrm{HI/OS})$. In the latter case, obviously we have $h_\Phi(\mathrm{OS/HI}) = -h_\Phi(\mathrm{OS}) < 0$, then both m_{OS} and m_{HI} are remagnetized simultaneously. The values of the fields $h_\Phi(\mathrm{HI/OS})$, $h_\Phi(\mathrm{OS/HI})$ can be read from Equation 1

$$h_\Phi(\mathrm{HI/OS}) = [J_1\, m_{\mathrm{IC}} \cos\theta - J_2\, m_{\mathrm{OS}} \sin\theta]\, f(\pi/2 - \theta) \tag{8}$$

$$h_\Phi(\mathrm{OS/HI}) = -J_2\, m_{\mathrm{HI}} \sin\theta \tag{9}$$

Finally, a necessary condition has to be fulfilled to reverse m_{IC}, i.e.

$$h_n < J_1\, m_{\mathrm{HI}} \cos\theta \tag{10}$$

As the change of magnetization is measured along the z-axis, Equation 10 can be seen as the necessary condition for bistability for the M_z–H_Φ hysteresis loop.

5. Results of the model

As was shown in Section 4, in principle, four scenarios are possible for the M_z–H_z hysteresis loop. The sequence of flipping of particular magnetic moments could be: (a) IC + HI + OS; (b) IC, HI + OS; (c) HI + OS + IC; (d) HI + OS, IC. The difference between cases (a) and (c) is due to different physical mechanisms, but the process of remagnetization is the same in both cases, i.e. all magnetic moments flip simultaneously. Similarly, for the M_z–H_Φ hysteresis loop, the possible scenarios are as follows: (a) OS + HI + IC; (b) OS, HI + IC; (c) OS + HI; (d) OS, HI; (e) HI + OS + IC, (f) HI + OS. If the inner core is reversed, it is reversed simultaneously with the helical interface. As for longitudinal hysteresis, scenarios are counted as different ones if different conditions for H^* are fulfilled.

It is natural to expect that sharp changes in the magnetic behaviour, shown in the experimental data, can be interpreted as changes of scenarios, e.g. from (a) to (b) etc. In such a case, two plots of H^* (σ) are expected to cross, and the system chooses the lower one. Then, we should observe a continuous plot $H^*(\sigma)$ with an incontinuous derivative. But for the M_z–H_z hysteresis we observe abrupt reduction of the switching field at a given value of applied stress. The conclusion is that for the longitudinal hysteresis, one scenario is likely to be active for the whole range of applied stress. To find this scenario, we have to choose between the following expressions for the switching field: (a) $h_z(\mathrm{IC})$, (b) h_z (HI/IC), (c) $h_z(\mathrm{HI})$ and (d) $h_z(\mathrm{IC/HI})$ (see Equations 2–5). The expression is of interest which could decrease rapidly with applied stress, as observed in the experiments (Fig. 2). In our opinion, the only agent which could be unstable is the distribution of magnetic moment between the helical interface and the outer shell. The argument is as follows: as magnetostriction is small, we expect that h_n and m_{IC} vary only smoothly with applied stress. Also we believe that the major contribution to H^* is given by exchange. This excludes case (d), as it is unlikely that $h_z(\mathrm{HI}) < h_z(\mathrm{IC/HI})$. Case (a) should also be excluded, because $m_r(\sigma)$ increases with stress, indicating that m_{HI} increases; if we adopt $H^* = h_z(\mathrm{IC})$. we got a contradiction to the experiment. Both cases (b) and (c) mean that a sharp reduction of H^* is due to the increase of the volume of a helically polarized surface between IC and OS. At the same time, the magnetic moment of the outer shell is reduced.

For a circular hysteresis loop, the bistability effect is absent in cases (c), (d) and (f). If the effect occurs, we have to choose between the following expressions for the switching field: (a) $h_\Phi(\mathrm{OS})$, (b) $h_\Phi(\mathrm{HI/OS})$ and (e) $h_\Phi(\mathrm{HI})$ (Equations 6–8). As the dependence of H^* (σ) is continuous, we admit that the change of scenario is possible near the value of applied stress $\sigma = 700$ MPa (see Fig. 4). The behaviour of $m_r(\sigma)$ indicates the behaviour of m_{HI} with applied stress. The former increase of $m_r(\sigma)$ up to 700 MPa excludes cases (a) and (b), because it is correlated to the reduction of the switching field with stress. Reduction of m_r above 700 MPa should be accompanied by an increase of H^*, if mechanism (e) has to be appropriate. Indeed, we observe a small increase of the switching field for $t_{\mathrm{ann}} = 360$ min, and even smoother enhancement for $t_{\mathrm{ann}} = 60$ min. This variation is much too smooth if compared with the sharp reduction of m_r with stress, but the two other mechanisms (a) and (b) again give results opposite to the experiment. Above 900 MPa, the bistability effect vanishes, which can be interpreted as the further reduction of m_{HI} and breaking of equation 10.

6. Discussion

To our knowledge, this approach is the first one where the strain dependence of bistability is investigated in a zero-magnetostrictive sample. We are interested in the conditions which need to be fulfilled to stabilize the effect in this kind of wire. Obviously, a necessary condition is the existence of an inner core. This condition is not fulfilled in as-quenched samples; there, magnetic anisotropy is perpendicular to the wire axis even at its centre. Also, magnetostriction is negative in as-quenched samples (although very small), and the inner core cannot be created by an external tensile stress.

Within our approach, we are able to find another necessary condition of the existence of bistability for the M_z–H_Φ hysteresis loop. This condition is the existence of a sufficiently high value of helically oriented magnetic moment in an interface between inner core and outer shell. We believe that this moment can be stabilized by annealing a wire in the presence of a torsional stress. This prediction can be verified experimentally.

In conclusion, stress and annealing-time dependence of the bistability effect has been investigated for the zero-magnetostrictive CoFeBSi amorphous wire. The results of the measurements can be quantitatively understood in the framework of a simple model of magnetic interaction between inner core and outer shell. There, the helically oriented interface plays a crucial role, and its magnetic state determines the values of the parameters of bistable behaviour.

Acknowledgements

One of the authors (K.K.) is grateful to the Ministry of Education and Science of Spain for financial support from the program "Profesor en Año Sabatico". This work has been supported by the C.I.C.Y.T. Project MAT 93-0437 and by the Excma Diputación Foral de Guipúzcoa.

References

1. K. MOHRI, F. B. HUMPHREY, K. KAWSHIMA, K. KIMURA and M. MIZUTANI, *IEEE Trans. Mag.* **26** (1984) 1789.
2. J YAMASAKI, F. B. HUMPHREY, K. MOHRI, H. KAWAMURA, H. TAKAMURE and R. MALMHALL, *J. Appl. Phys.* **63** (1988) 3949.
3. R. HASEGAWA, *J. Magn. Magn. Mater.* **100** (1992) 1.
4. C. GOMEZ-POLO, T. REININGER, M. VAZQUEZ and H. KRONMULLER. *IEEE Trans. Magn.* **29** (1993) 3481.
5. C. GOMEZ-POLO, M. VAZQUEZ, T. REININGER and H. KRONMULLER, in "Trends in Non-crystalline Solids", edited by A. Conde, F. Conde and M. Millan (World Scientific, Singapore, 1992) p. 421.
6. M. VAZQUEZ, C. GOMEZ-POLO and D. – X. CHEN, *IEEE Trans. Mag.* **28** (1992) 3147.
7. M. VAZQUEZ, J. GONZALEZ, J. M. BLANCO, J. M. BARANDIARAN, G. RIVERO and A. HERNANDO, *J. Magn. Magn. Mater.* **96** (1991) 321.
8. J. M. BLANCO, P. ARAGONESES, J. GONZALEZ, A. HERNANDO, M. VAZQUEZ, C. GOMEZ-POLO, J. M. BARANDIARAN, P. T. SQUIRE and M. R. J. GIBBS, in "Proceedings on the 1st International Conference on Magnetoelastic Effects and Applications", Naples, May 1993, edited by L. Lanotte (Elsevier, Amsterdam, 1993) p. 253.
9. K. KULAKOWSKI, J. GONZALEZ and P. ARAGONESES, to be published.
10. J. GONZALEZ, J. M. BLANCO, M. VAZQUEZ, J. M. BARANDIARAN and A. HERNANDO, *J Appl. Phys.* **70** (1991) 6522.
11. P. ARAGONESES, J. M. BLANCO, J. GONZALEZ and M. VAZQUEZ, *IEEE Trans. Magn.* **29** (1993) 3475.
12. S. CHIKAZUMI "Physics of magnetism" (Krieger, Huntington, 1978) p 188.

Received 23 September 1994
and accepted 17 May 1995