Materials Science and Engineering A 521–522 (2009) 201–204

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Magnetomechanical damping in Ni–Fe–Ga poly and single crystals

M.L. Corró [a,*], S. Kustov [a], E. Cesari [a], Y.I. Chumlyakov [b]

[a] Department of Physics, University of Illes Balears, Carretera de Valldemossa km 7.5, Palma de Mallorca E07122, Spain
[b] Siberian Physical-Technical Institute, Novo-Sobornaya Sq., 1, 634050, Tomsk, Russia

ARTICLE INFO

Article history:
Received 16 August 2008
Accepted 16 September 2008

Keywords:
Magnetomechanical damping
Ferromagnetic shape memory alloys
Anelasticity
Acoustic methods

ABSTRACT

Magnetomechanical damping has been studied in poly and single crystalline Ni–Fe–Ga ferromagnetic shape memory alloys in the austenitic state, with emphasis on the non-linear hysteretic component. The experiments were performed at an ultrasonic frequency, over a wide range of strain amplitudes, at room temperature with different transverse polarizing fields and from 255 to 365 K with different axial polarizing fields. We found that polycrystalline samples demonstrate higher damping level than single crystals. The contribution of the hysteretic magnetomechanical damping is low in polycrystals and damping properties in the austenite are predominantly controlled by existing defects, like dislocations, grain boundaries, and cracks. Single crystalline samples are characterized by substantially lower values of the total damping due to their higher degree of structural perfectness. In contrast to the polycrystals, the non-linear damping in the austenitic state is associated in single crystals with the hysteretic magnetomechanical damping.

1. Introduction

Shape memory alloys show a structural phase transition called thermoelastic martensitic transformation. The martensitic transformation is behind such effects present in these alloys as large reversible mechanical deformations (superelasticity), the shape memory effect and high damping, due to the high concentration and mobility of defects in the martensitic state [1]. Ferromagnetic shape memory alloys, in addition to previous properties, can exhibit large magnetic field induced strains [2,3] in comparison with other ferromagnetic materials, which is the reason to propose them as actuators. Ferromagnets can demonstrate high damping state, which has a magnetomechanical origin and stems from several mechanisms associated with the oscillatory displacement of magnetic domain boundaries. However, some basic characteristics of ferromagnetic shape memory alloys are not well known, particularly the damping properties. Internal friction has been studied in ferromagnetic shape memory alloys like Ni–Mn–Ga [4,5] and Ni–Mn–Fe–Ga [6]. As far as the authors are aware, no attempt has been undertaken to evaluate the contribution of magnetomechanical damping (MMD) to the damping properties of ferromagnetic shape memory alloys. In the present work, data on internal friction in the parent phase of Ni–Fe–Ga will be reported and we will be mostly concerned with the estimation of hysteretic amplitude-dependent MMD.

2. Experimental technique and materials

A recently designed experimental setup [7] based on a piezoelectric composite oscillator method [8] was used for the experimental investigations of internal friction and Young's modulus defect for resonant longitudinal oscillations at ultrasonic frequencies of about 100 kHz. A modification of this technique, referred to as mechanomagnetic spectroscopy [9], allowed us to measure simultaneously mechanically induced variations of the induction (the inverse magnetostriction effect) and anelastic properties (logarithmic decrement δ and Young's modulus defect $\Delta E/E$) as a function of oscillatory strain amplitude ε_0. The experimental setup permitted to apply a uniform axial field with intensity up to 12 kA/m using a 400-mm-long solenoid. For simultaneous measurements of damping and stress-induced induction (also in the axial field) a four-component oscillator was used with an intermediate rod of an Al–Mg alloy between the quartz transducer and the sample in order to separate piezoelectric and ferromagnetic parts of the oscillator.

The measurements were also made in a transverse field up to 1 T produced by an electromagnet. In that case, in order to obtain a reasonable homogeneity of the field, the gap between the 40 mm diameter poles was fixed at about only 4 mm. To avoid possible displacements of the sample inside the gap by applied field, the quartz transducer was additionally fixed in the positions of strain nodes. A classical three-component oscillator was used for the measurements in transverse field.

Ni–19Fe–27Ga poly and Ni–21.5Fe–27Ga (at.%) single crystals were studied. The Curie (T_C) and start of the direct martensitic

* Corresponding author. Tel.: +34 971172535; fax: +34 971173426.
E-mail address: miguel.corro@uib.cat (M.L. Corró).

0921-5093/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2008.09.155

transformation (M_S) temperatures were around 299 and 278 K for the former alloy and 355 and 155 K for the latter. Rod-shaped samples (1.5 mm × 1.5 mm × 10 mm) were produced by spark cutting, annealed for 15 min at 1120 K (polycrystal) or 1370 K (single crystal), and air cooled in order to obtain a high degree of atomic order and well defined para- to ferromagnetic transitions. The three axes of the single crystalline sample were along ⟨1 0 0⟩ directions. All samples were initially in thermally demagnetized state.

3. Results and discussion

3.1. Polycrystals

In Fig. 1(a) the strain amplitude dependence of the decrement δ is shown for a polycrystalline sample under different transverse polarizing fields up to 800 kA/m. Clearly, application of the polarizing field has a marginal effect on damping: only a slight increase of the decrement values with respect to the demagnetized state can be discerned.

The total measured decrement $\delta(\varepsilon_0)$ includes the linear (strain-amplitude-independent) low-amplitude background δ_i and the non-linear (strain-amplitude-dependent) component $\delta_h(\varepsilon_0)$: $\delta(\varepsilon_0) = \delta_i + \delta_h(\varepsilon_0)$. Fig. 1(b) depicts the non-linear part $\delta_h(\varepsilon_0)$ of the total decrement on a double logarithmic scale. Apparently, a polarizing field has no notable effect on the amplitude-dependent damping of the polycrystalline alloy, despite the high values of the applied field close to the saturating ones [10]. Since the MMD is determined as the difference between the damping in the demagnetized or partially magnetized states and under the saturating field, this fact points to a negligible role of the hysteretic MMD in the total damping of ferromagnetic polycrystalline Ni–Fe–Ga alloys. According to Fig. 1(b), the strain-amplitude-dependent damping

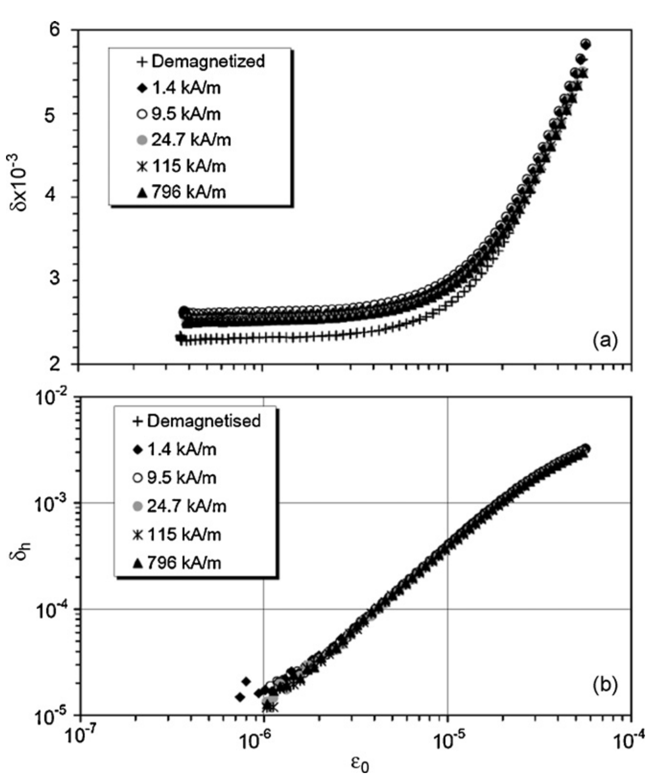

Fig. 1. Strain amplitude dependence of the total internal friction δ (a), and its amplitude-dependent component δ_h (b), for a Ni–19Fe–27Ga (at.%) polycrystal at room temperature (T = 293 K, austenite), under different transverse polarizing fields up to 796 kA/m.

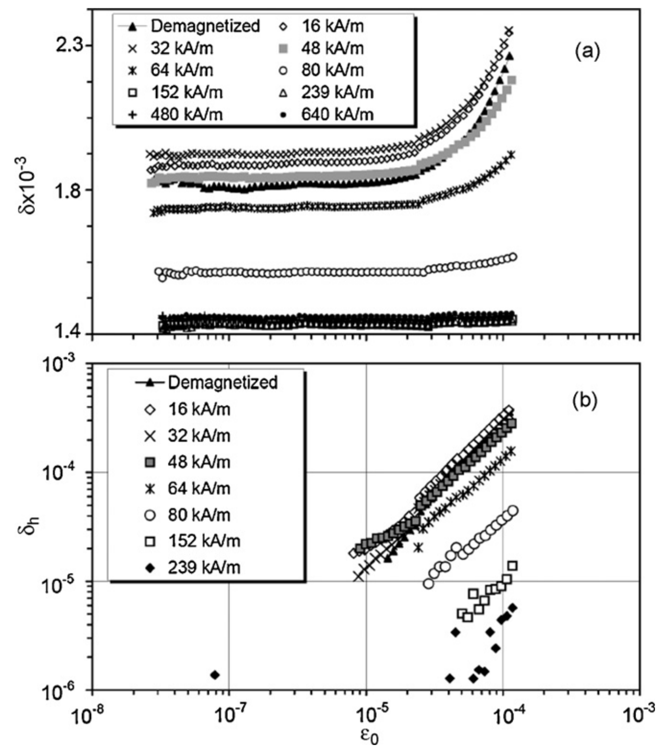

Fig. 2. Strain amplitude dependence of the total internal friction δ (a), and its amplitude-dependent component δ_h (b), for a Ni–21.5Fe–27Ga (at.%) single crystal at room temperature (T = 300 K, austenite), under different transverse polarizing fields up to 796 kA/m.

over a wide range of strain amplitudes is a power function

$$\delta_h(\varepsilon_0) \propto \varepsilon_0^n \tag{1}$$

with saturation at a strain amplitude of around 2×10^{-5}. The strain exponent takes the value $n \cong 1.5$, which clearly disagrees with the slope $n = 1$ expected for the low- and moderate-strain amplitude Rayleigh region of the hysteretic MMD [11–13]. Thus, the contribution of the hysteretic MMD to the strain-amplitude-dependent damping of polycrystalline Ni–Fe–Ga alloy is very low in the parent phase.

3.2. Single crystals

Fig. 2, similar to Fig. 1, shows the strain amplitude dependence of the total decrement (a) and its amplitude-dependent part (b) for a single crystalline sample for different transverse polarizing fields. Two salient features should be mentioned. First, the level of amplitude-dependent damping in single crystals is an order of magnitude lower than in a polycrystal for similar values of strain amplitude, see Figs. 1(b) and 2(b). Second, the damping in single crystal demonstrates a strong effect of polarizing field: both the low-amplitude background and the strain-amplitude-dependent decrement present non-monotonous dependence on polarizing field: they first increase slightly for polarizing fields up to 32 kA/m and then decrease dramatically. For instance, the amplitude-dependent component of damping drops nearly two orders of magnitude for a field of 240 kA/m as compared to the demagnetized state (Fig. 2(b)) and becomes practically indistinguishable in the total damping Fig. 2(a). Similar to the results for polycrystalline samples, the strain-amplitude-dependent decrement can be fitted with a power law, Eq. (1). However, now the strain exponent is $n \approx 1$, demonstrating behavior typical of the magnetomechanical damping in the Rayleigh region.

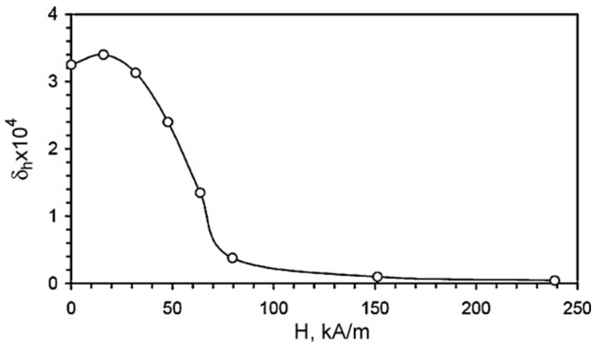

Fig. 3. Amplitude-dependent internal friction (δ_h) for a Ni–21.5Fe–27Ga (at.%) single crystal, as a function of transverse polarizing field, at room temperature (T = 300 K, austenite).

Fig. 3 depicts the field dependence of the strain-amplitude-dependent decrement for strain amplitude of 10^{-4}, obtained from a vertical cross-section of data in Fig. 2(b). As mentioned before, the damping first increases slightly and then drops rapidly practically to a zero level which is typical of the hysteretic MMD [12]. Thus, several observations point to a substantial contribution of MMD to the damping in single crystal samples. Moreover, the strain-amplitude-dependent decrement appears to have purely magnetomechanical origin, since it is completely suppressed by polarizing field, leaving no space for other mechanisms.

In order to check this conclusion, the temperature spectra of damping in a single crystalline sample were studied below and above the Curie temperature under different values of axial polarizing fields. The temperature dependence of the amplitude-dependent part of the decrement is represented in Fig. 4. Experimental data demonstrate the existence of a low, practically field-independent, level of amplitude-dependent damping of around 3×10^{-5} above the Curie temperature (which is around 355 K) and below 290 K. The latter temperature represents a magnetic transition in this alloy which is characterized by a strong decrease of inverse magnetostriction below the transition temperature [14]. Since inverse and direct magnetostriction effects are thermodynamically related [15], a decrease of inverse magnetostriction means a decrease of direct magnetostriction. The hysteretic MMD in the Rayleigh region, following the most widely used internal stress distribution theory of Smith and Birchak [11], is given by

$$\delta_h(\varepsilon_0) \propto \frac{E^2 \lambda \varepsilon_0}{\sigma_i^2}, \quad (2)$$

where E is the Young modulus, λ is the easy axis magnetostriction and σ_i is the average internal stress in the sample. Following Eq. (2), a decrease of magnetostriction below the magnetic transition temperature produces a decrease of δ_h.

The level of non-linear damping between T_C and the magnetic transition temperature is strongly affected by polarizing field: it increases slightly for low polarizing field and then it drops rapidly to rather low values, similar to the effect observed in the transverse magnetic field, Fig. 3. However, the suppression of the non-linear damping in the axial field occurs for much lower field values than in the transverse direction, Figs. 2(b) and 3. This difference in the characteristic values of axial and transverse magnetic fields should be attributed to substantially different demagnetizing factors along and across a rather long sample. The temperature spectra in the case of axial field were measured using a four-component oscillator with an intermediate Al–Mg alloy rod, and the field-independent low level of the amplitude-dependent damping above the T_C is related to the non-magnetic non-linear damping of the quartz transducers with the intermediate Al–Mg rod.

A comparison of results obtained for single and polycrystalline samples of Ni–Fe–Ga alloys points to a dramatic change of the origin of non-linear damping: in polycrystals the high level of damping is not related to the hysteretic MMD, whose contribution is negligible; in single crystals, on the contrary, rather low values of the total non-linear damping are predominantly due to the hysteretic MMD. Both these features can be explained from the same viewpoint, assuming that brittle polycrystalline samples of Ni–Fe–Ga alloy have high concentrations of defects like dislocations and probably even microcracks. These defects, on one hand, are responsible for the high value of non-linear damping in polycrystals. On the other hand, they create high internal stresses. Following Eq. (2),

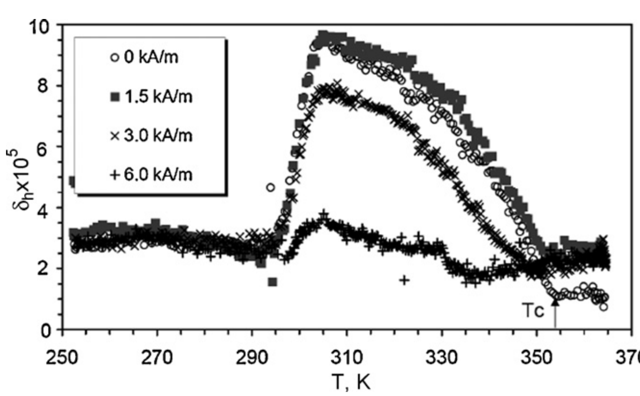

Fig. 4. Temperature dependence of the amplitude-dependent component of the decrement δ_h in the austenitic phase of Ni–21.5Fe–27Ga (at.%) single crystal. The measurements were performed with axial polarizing magnetic fields of 0, 1.5, 3.0 and 6.0 kA/m. Data were obtained as the difference between the total decrement for strain amplitude of 4×10^{-5} and amplitude-independent background for strain amplitude of 10^{-6}. Data are shown for decreasing T. The Curie temperature, T_C, is indicated by the arrow.

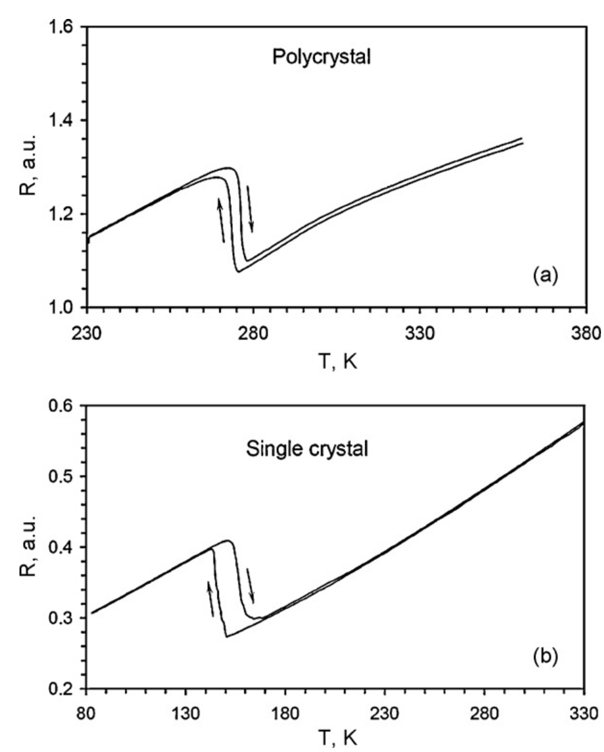

Fig. 5. Resistance in a cooling–heating cycle through the martensitic transformation, for both poly (a) and single (b) crystals of Ni–Fe–Ga alloys.

internal stresses strongly suppress the hysteretic MMD. Single crystals, on the contrary, are characterized by a low concentration of defects and a low level of the total damping, in which the hysteretic MMD plays a determining role.

Data on electrical resistance support the conclusion about the essential role of defects in polycrystals and their minor role in single crystals. Fig. 5 shows the results of resistance measurements for single and polycrystalline samples similar to those used in damping studies. The fact relevant to the present work is that each martensitic transformation leads to a substantial irreversible increase of the resistance of polycrystalline samples, Fig. 5(a), whereas such irreversibility can hardly be discerned for single crystalline one, Fig. 5(b). This fact evidences the existence of a higher concentration of defects in polycrystalline samples, which are responsible for the further increase of their density with each martensitic transformation, leading to the irreversible increase of resistance. On the contrary, the density of defects is much lower in single crystalline samples and, therefore, production of defects during the transformation remains much less intense than in polycrystals.

4. Conclusions

Different behaviors of δ and δ_h under polarizing fields have been found for Ni–Fe–Ga poly and single crystals in the ferromagnetic austenitic phase. The defects existing in polycrystals produce much higher values of the non-linear damping (one order of magnitude) than in single crystals and suppress hysteretic magnetomechanical damping, presumably through the high values of internal stresses. In contrast, the total non-linear damping is much lower in single crystals. Hysteretic magnetomechanical damping plays a determining role in this case.

Acknowledgements

Partial financial support from DGI (projects MAT2005-00093 and MAT2006-28193E) and from Govern de les Illes Balears (ref. PCTIB-2005GC2-02) is acknowledged.

References

[1] J. Van Humbeeck, Mater. Sci. Forum 366–368 (2001) 382–415.
[2] K. Ulakko, J.K. Huang, C. Kantner, R.C. O'Handley, V.V. Kokorin, Appl. Phys. Lett. 69 (1996) 1966–1968.
[3] R.C. O'Handley, S.J. Murray, M. Marioni, H. Nembach, S.M. Allen, J. Appl. Phys. 87 (2000) 4712–4717.
[4] E. Cesari, V.A. Chernenko, V.V. Kokorin, J. Pons, C. Seguí, Acta Mater. 45 (1997) 999–1004.
[5] V.G. Gavriljuk, O. Söderberg, V.V. Bliznuk, N.I. Glavatska, V.K. Lindroos, Scr. Mater. 49 (2003) 803–809.
[6] W.H. Wang, X. Ren, G.H. Wu, Phys. Rev. B 73 (2006) 092101-1–092101-4.
[7] S. Kustov, S. Golyandin, A. Ichino, G. Gremaud, Mater. Sci. Eng. A 442 (2006) 532–537.
[8] G. Gremaud, S. Kustov, Ø. Bremnes, Sci. Forum 366–368 (2001) 652–666.
[9] S. Kustov, F. Masdeu, E. Cesari, Appl. Phys. Lett. 89 (2006) 061917-1–061917-3.
[10] K. Oikawa, T. Ota, Y. Tanaka, H. Morito, A. Fujita, R. Kainuma, K. Fukamichi, K. Ishida, Appl. Phys. Lett. 81 (2002) 5201–5203.
[11] G.W. Smith, J.R. Birchak, J. Appl. Phys. 39 (1967) 2311–2316.
[12] V.F. Coronel, D.N. Beshers, J. Appl. Phys. 64 (1988) 2006–2015.
[13] J. Degauge, Mater. Sci. Forum 366–368 (2001) 453–482.
[14] M.L. Corró, S. Kustov, E. Cesari, F. Masdeu, Y.I. Chumlyakov, Proc. Int. Conference on Martensitic Transformations'08, The Minerals, Metals & Materials Society, USA, in press.
[15] R.M. Bozorth, Ferromagnetism, IEEE Press, Piscataway, NJ, USA, 2003, pp. 729–744.