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

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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 of reversible mechanical deformations (superelasticity), the shape memory effect and high damping, due to the high concentration 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 δE/δE) as a function of oscillatory strain amplitude ε0. 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 (TC) and start of the direct martensitic
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 $\delta$ 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 $δ(\varepsilon_0)$ includes the linear (strain-amplitude-independent) low-amplitude background $δ_i$ and the non-linear (strain-amplitude-dependent) component $δ_h(\varepsilon_0)$: $δ(\varepsilon_0) = δ_i + δ_h(\varepsilon_0)$. Fig. 1(b) depicts the non-linear part $δ_h(\varepsilon_0)$ 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 over a wide range of strain amplitudes is a power function

$$δ_h(\varepsilon_0) \propto \varepsilon_0^n$$

with saturation at a strain amplitude of around $2 \times 10^{-5}$. The strain exponent takes the value $n \approx 1.5$, 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 alloys 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 component (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.

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

![Fig. 2. Strain amplitude dependence of the total internal friction $\delta$ (a), and its amplitude-dependent component $\delta_h$, 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.](image)
Fig. 3. Amplitude-dependent internal friction ($\delta_h$) for a Ni–21.5Fe–27Ga (at.%) single crystal, as a function of transverse polarizing field, at room temperature ($T = 300$ K, austenite).

Fig. 4. Temperature dependence of the amplitude-dependent component of the decrement $\delta_h$ 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 $4 \times 10^{-5}$ 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.

is given by

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

(2)

where $E$ is the Young modulus, $\lambda$ is the easy axis magnetostriction and $\sigma_i$ is the average internal stress in the sample. Following Eq. (2), a decrease of magnetostriction below the magnetic transition temperature produces a decrease of $\delta_h$.

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),
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 $\delta$ and $\delta_s$ 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.

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References