Magnetostriction and damping of forced vibrations in Fe-Mo single and polycrystal alloys

I.S. Golovin[a,b *], D.G. Chubov[a], A.D. Berezner[c], D.L. Schlagel[d], H.W. Chang

[a] National university of science and technology "MISiS", Leninsky ave.4, 119049 Moscow, Russia
[b] Moscow Polytechnic University, B. Semenovskay 38, 107023 Moscow, Russia
[c] Derzhavin Tambov State University, Internatsionalnaya Str. 33, 392000 Tambov, Russia
[d] Division of Materials Science and Engineering, Ames Laboratory, Ames, IA, 50011 USA
[e] Department of Physics, National Chung Cheng University, Chia-Yi, 621 Taiwan

* i.golovin@misis.ru

Abstract:

Magnetostriction and damping of forced vibrations in Fe-Mo single and polycrystal alloys is studied and analyzed with respect to existing approaches and experimental data. It is shown that more complicated dependence (compared with linear dependence predicted by Smith and Birchak) between damping capacity and magnitostriction of a sample takes place. Our study suggests that more factors should be considered to provide a better correlation between the magnetic and magnetomechanical characteristics of an alloy.

Keywords: Fe-Mo, damping, magnetostriction, single and polycrystals

1. Introduction

The addition of both magnetic (Cr, Mo, V, W) and nonmagnetic (Al, Ga, Ge) elements into α-Fe significantly enhances magnetostriction of Fe-based alloys. The tetragonal magnetostriction $(3/2)\lambda_{100}$ for Fe–Al [1,2], Fe-Cr [3], Fe–Ga [4], Fe–Ge [5], Fe-Mo [6], and Fe-W [1,2,7] increases monotonically with the solute concentration in the bcc α-Fe single phase region and reaches a maximum, which can depend on the thermal history, near the solubility limit. The large tetragonal magnetostriction in these Fe–X alloys is associated with a combination of increased magnetoelastic coupling and a softening of the shear elastic constant $c' = ½(c_{11}-c_{12})$ [7, 8].

The linear ratio between damping capacity due to magneto-mechanical hysteresis (Q_h^{-1}) and saturation magnetostriction (λ_S) was proposed by Smith and Birshak [9]: $Q_h^{-1} \sim \lambda_S E/\sigma_i$, where E is the elastic modulus and σ_i is the mean value of internal stresses.. The main acting mechanism of damping in Gentalloys (High damping Fe-Mo alloys have the trade name Gentaloy) is magneto-mechanical damping [10,11]. H. Masumoto et al. studied damping capacity of polycrystalline Fe-Mo alloys ranging in concentration between 0 and 16% Mo using free decay vibrations in torsion pendulum. They reported that Fe-6Mo alloy exhibits the highest total Q_h^{-1} value of 0.058 when annealed at 1200°C for 1 h. For the alloys with 10-16%Mo, Q_h^{-1} increases when the sample is air- or water-quenched compared to furnace-cooling, suggesting that precipitation of the non-ferromagnetic β-phase in the matrix of the ferromagnetic α-phase is substantially suppressed by quenching.

M. Huang et al. [12] investigated the magnetostrictive and elastic properties for single crystalline $Fe_{100-x}Mo_x$ alloys with 2<x<12. The tetragonal magnetostriction of slowly cooled and quenched Fe–Mo alloys follows similar trends to other Fe-based alloys. The tetragonal magnetostriction increases with Mo composition to a maximum and then decreases due to the formation of a second phase. Quenching the crystals from high-temperature in the A2 phase region increases the magnetostriction for alloys with a Mo composition beyond the room temperature solubility limit. The nanoprecipitates are formed with increasing Mo% due to the decomposition of A2 → A2 + C14 ($P6_3/mmc$). Short-term aging leads to formation of C14 phase nucleation which, according Ref [6], increases magnetoctriction.

In contrast to work by Thuanboon et al. [13], the $c' = \frac{1}{2}(c_{11}-c_{12})$ constant for single crystal Fe-15Mo alloy was found to be the same as that of pure α-Fe. This result supports the viewpoint that the origin of the increase in magnetoelasticity, with Mo additions to α-Fe, is different from those found with Al, Ga, and Ge additions in which a pronounced softening of the shear elastic constant c′ takes place. This suggests that the enhanced coupling is solely due to different ground-state electronic structures. While the d-shell is fully occupied in both elemental Ga and Ge, the d-shell ($3d^{10}$) is half-filled in elemental Mo ($4d^5$). [Question: What does the ½ filled shell allow? A ½ filled shell is also stable but has unfilled spots that may allow more hybridization, valence and conduction band sharing etc. that a full shell may not. How might the potential changes brought about by a ½ filled shell affect the magnetostriction and damping?]

This paper continues our studies of damping capacity under forced bending vibrations and its correlation with magnetostriction in α-Fe based alloys: Fe-Al [14], Fe-Ga [15], Fe-Ge [16], Fe-Cr [17,18]. In this paper we investigate Fe-Mo single and polycrystals with similar chemical composition with respect to their amplitude dependent damping at forced vibrations and magnetostriction for Fe-5.5%Mo poly- and single crystals.

2. Experimental Procedure

Single crystal (SC) and directionally solidified (DS) samples were synthesized at the Materials Preparation Center, Ames Laboratory, USDOE. See www.mpc.ameslab.gov. Appropriate quantities of electrolytic grade iron (99.99% purity) and electronic grade molybdenum (99.99% purity) were arc melted several times into buttons under an argon atmosphere. Single crystal growth was done using a modified Bridgman technique in a resistance furnace. The ingots were annealed at 1000 °C (to be within the single A2 phase region at that concentration) under high purity argon for 168 h to homogenize the composition and releave stresses left by the crystal growth. The ingot was cooled at 10 °C/min which is considered slow cooled. Laue back-reflection diffraction, using a PANalytical PW1830 generator with Photonic Science camera, was used to orient (100) and (110) samples that were sectioned from the ingot for damping capacity and magnetostriction measurements. Chemical composition of all alloys was measured by energy-dispersive X-ray spectroscopy (EDS)to be Fe-(5.0-5.5)wt.%Mo.

Mechanical spectroscopy is a simultaneous test of anelastic ($tg\varphi=Q^{-1}$, internal friction, φ is the phase lag between the applied cyclic stress σ and the resulting strain ε: $\sigma=\sigma_0\cos(\omega t)$ and $\varepsilon=\varepsilon_0\cos(\omega t+\varphi)$) [Question: is ε_0 initial strain? Later in the paper it is called deformation. Please define this and ω in the text]and elastic (Young's modulus E) properties amplitude (amplitude-dependant internal friction or ADIF) of vibrations ($0.0004 < \varepsilon_0,\% < 0.2$). The ADIF tests were carried out in our study using a commercial dynamical mechanical analyzer (DMA Q800 TA Instruments) and forced vibration of clamped samples in a single cantilever mode; sample dimension were approximately 17.5×(2.7-4.4)×(0.7-1.2) mm. The example is shown in Fig. 1. The absolute values of elastic modulus are not very precise if measured on a DMA apparatus [18]; however, the main reason to present $E(\varepsilon_0)$ curves is to demonstrate relative change of modulus (in arbitrary units) with variation in vibration amplitude.

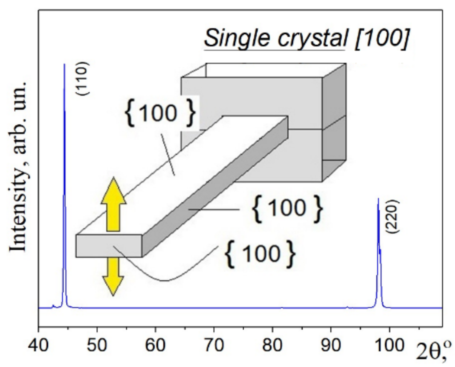

Fig. 1. Single cantilever clamping of a single crystal. {100} sampledirections independently verified by XRD.

Magnetization measurements were performed at room temperature by using a vibrating sample magnetometer VSM-130. The room temperature magnetostriction was measured by two devices:

(i) the strain gauge method (CEA-05-250UN-350 strain gage from Vishay Intertechnology, Inc.) in a wide range of magnetic field from 0 to 6 kOe.

(ii) a hand-made setup using a capacitive dilatometer: strain gauge method and two solenoids applying magnetic field up to 5 kOe.

The longitudinal ($\lambda_{||}$) and transverse ($\lambda_{\perp}$) magnetostriction correspond to the strain measured parallel and perpendicular to the applied magnetic field. The total magnetostriction is given by $\Delta\lambda = \lambda_{\parallel} - \lambda_{\perp}$.

3. Results and Discussion

The ADIF ($Q^{-1}(\varepsilon_0)$) curves for polycrystalline sample cut from directly solidified ingot are shown in Fig. 2a. The ADIF curves show repeatability in six subsequent runs (runs n. 1-3 with ε_0 = 0.07% followed by runs n. 4-6 with ε_0 = 0.14%) damping peak (at ε_0 = 0.01-0.03%) and corresponding ΔE minimum (at ε_0 = 0.04-0.07%). The E values are given in the Fig.1 in arbitrary units which are proportional but not equal to absolute values as discussed in [18]. Increase in maximal deformation from 0.07 to 0.14% leads to a little increase in interal friction (IF) values for all amplitudes. There are two possible reasons for this effect: (i) increase in dislocation density after deformation with ε_0 = 0.14% or (ii) increase in local internal stresses in the alloy, which may change mobility of magnetic domain walls (MDW). The second version is indirectly supported by the observation of the peaks shifting to higher amplitudes.

Following Smith and Birchak's (SB) approach [19] internal stresses can be estimated as 25 MPa in tests with ε_0 = 0.07% and 30 MPa in tests with ε_0 = 0.14%. The contribution of dislocations, i.e. non-magnetic contribution, can be distinguished by applying a saturation magnetic field. This option is not included in our DMA Q800 set up and does not work well using external Nd-Fe-B magnets [15]. However, a magnetic field can be easily applied at the torsion pendulum using an electrical coil, see e.g. Refs. [20,21] to ensure that nonmagnetic contributions to the total damping in ferromagnetic materials is about one order of magnitude smaller compared to magneto-mechanical damping. It is also notable, that damping capacity as measured by forced bending vibrations (including tests on DMA) are always lower compared with tests on torsion pendulum: e.g. in this paper $Q_{max}^{-1} \sim 0.017$ (Fe-5Mo) against 0.058 (Fe-6Mo) as reported in [11].

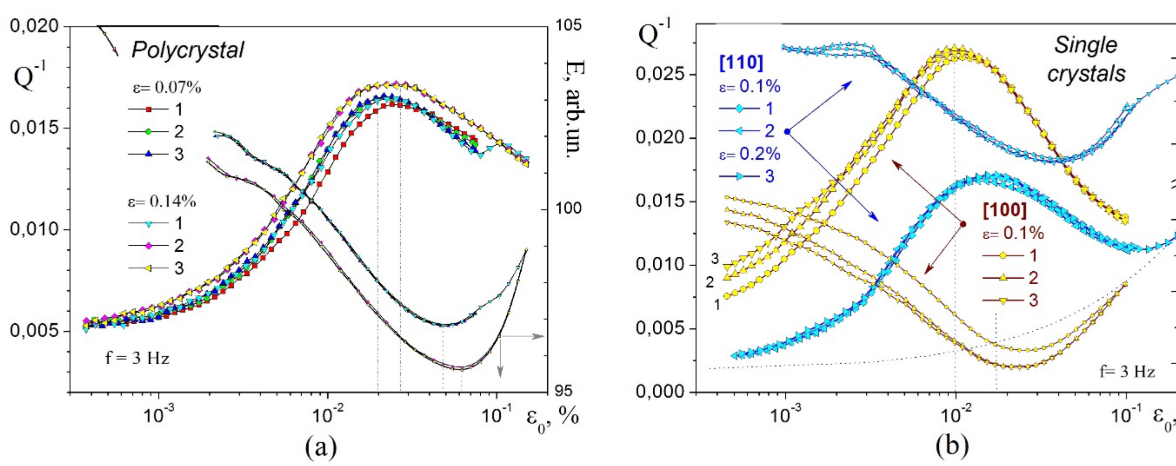

Fig. 2. ADIF curves for Fe-Mo samles: (a) polycrystal, (b) single crystal

ADIF curves for different orientation of single crystals are shown in Fig. 2b (schematic of sample clamping is presented in Fig. 1). The [100] sample, i.e. sample orientated along the magnetically easy axis, has higher damping and lower strain at the damping peak, which is sensitive on the up-hill side of a peak to the number of previous tests, and has lower elastic modulus as compared with the [110] orientated sample. Maximal damping and peak strain of the polycrystal sample are roughly similar to the [110] orientated sample, while its background (at $\varepsilon < 10^{-3}$) is slightly higher. This is attributed to contribution from the grain boundaries in the polyctystal.

Magnetostriction of the same alloys (λ(H) dependences) is presented in Fig. 3(a-c) (Vishay Intertechnology setup). Fig. 3d illustrates the $\Delta\lambda/\Delta H$ dependences in the first quadrant with higher precision (self made equipment). Magnetism, (M_S – saturation magnetization and H_C – coercive force at RT) magnetostriction (λ_S – satutation parallel magnetostriction and total magnetostriction $\Delta\lambda = \lambda_{\parallel} - \lambda_{\perp}$, H_S – saturation magnetic field, H_{eff} – magnetic field which corresponds to maximum at $\lambda(H)$ dependence, $d\lambda/dH$ maximum rate of change of magnetostraction over the field) and magnetomechanical (Q_{max}^{-1}, ε_{max}) characteristics are collected in Table 1. One can see the correlation between maximal damping (Q_{max}^{-1}) and saturation magnetostriction λ_S as proposed by SB theory. On the other hand the maximum mobility of domain walls ($\Delta\lambda/\Delta H$) is most important for damping of mechanical vibration.

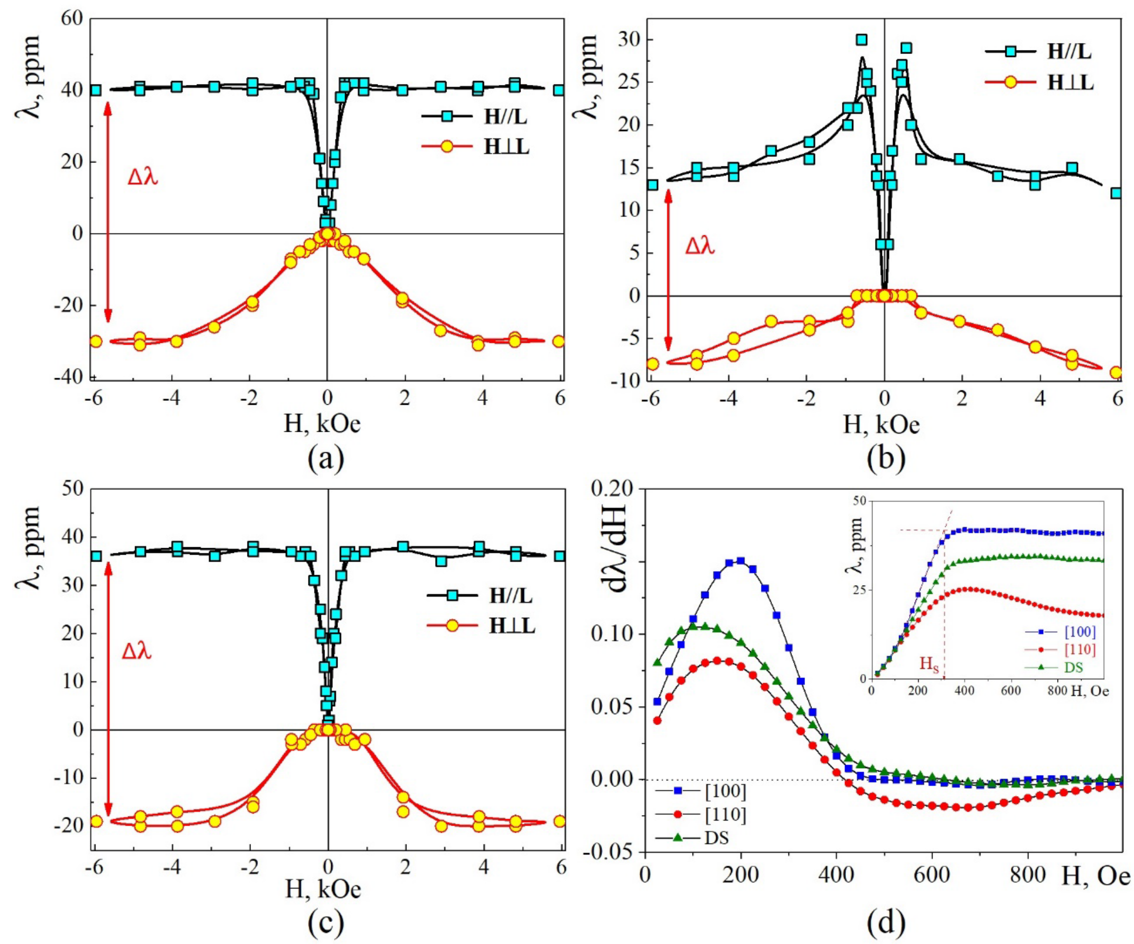

Fig. 3. Magnetostriction curves for Fe-Mo samples: (a) Fe-5.5Mo SC [100], (b) Fe-5.3Mo SC [110], (c) Fe-5Mo DS (Vishay Intertechnology setup) and (d) Fe-Mo all compositions listed here (self made equipment)

Table 1. The values analyzed from the magnetostriction curves for the Fe-Mo SC and DS samples

Sample	M_S, emu/g	H_c, Oe	λ_S, ppm	H_S, Oe	$\Delta\lambda$, ppm	H_{eff}, Oe	$\Delta\lambda/\Delta H$, ppm/Oe	Q_{max}^{-1}	ε_{max}, $\times 10^{-4}$

DS	201	22	35	340	56	130	0.10	0.017	3
SC[100]	-	-	40	310	70	200	0.15	0.027	1
SC[110]	-	-	30	335	21	150	0.08	0.016	2

It is easy to notice that damping in single Fe-5Mo crystals (this paper: Q_m^{-1}=0.027 bending forced vibrations) is significantly lower (4.8 times) than in an Fe-18Ga single crystal (Q_m^{-1}=0.13 torsion forced vibrations) recently reported in [21]. The ratio for highest magnetostrictions ([100] for bending and [111] for torsion) is nearly the same (40 *vs.* 200 ppm) as well as the saturation magnetization reported using torsion is higher for [100]. The value of strain at which maximal damping is observed with bending (1×10^{-4} for [100]) is lower than those observed for torsion (4×10^{-4} for [111]). Thus, the problem of comparing damping capacity of an alloy measured under different scheme of loading remains open and needs further analysis.

Total deformation of a ferromagnetic sample $\varepsilon_{tot} = \varepsilon_{el}+\varepsilon_{unel}+\lambda$, where ε_{el} is the elastic component of deformation, ε_{unel} is anelastic (time dependent) part of deformation from the non-magnetic relaxation processes, and λ is the unelastic deformation due to contribution from magnetic processes [22]. Assuming reversable strain and using both Joule λ=f(H) [23] and Villary M=f(ε_0) [24] laws, the dependence of damping (Q^{-1}) on the sample strain during bending (ε_0) and magnetostriction of the alloy (λ) can be written in the form (details in Supplementary material):

$$Q^{-1} = \tan\left(\omega t - \arccos\left(\frac{\varepsilon_0+\lambda}{\varepsilon_0}\right)\right). \qquad (1)$$

[I do not think *t* has been defined yet]Magnetostriction, λ, depends on magnetic properties of the alloy, which in turn are dependent on structure (homogeneity/heterogeneity of crystalline lattice, size and shape of magnetic domains and domain walls) thermal history, tempetarue (T) and applied stress or magnetic field. In first approximation one can write:

$$\lambda(H) = \frac{x_0}{H_S mA(1-\cos(\theta))}\left(cth\left(\frac{\mu_0 m(H+\gamma M)}{k_B T}\right) - \frac{k_B T}{\mu_0 m(H+\gamma M)}\right) \qquad (2a)$$

and

$$\frac{d\lambda}{dH} = \frac{1}{H_S Am(1-\cos(\theta))}\left(-\frac{\mu_0 m}{k_B T sh^2\left(\frac{\mu_0 m(H+\gamma M)}{k_B T}\right)} + \frac{k_B T}{\mu_0 m(H+\gamma M)^2}\right), \qquad (2b)$$

[use *mA* in denominator of first term to be consisten with equation 2a. Also define *c*, *h*, and *s*]where H_S is the saturation field, μ_0 is the permeability (in vacuum), k_B is the Boltzmann constant, *M* is a magnetization of a sample, *m* is a unit of volume, θ is angle between the directions of *H* and *M*, γ is the internal exchange parameter, T is temperature.

Thus, the equations (1) and (2) underline, similarly to experimental data, a more complicated dependence (not simple linear as in SB model) between damping capacity and magnetistriction. Our study suggests that more factors compared with Smith and Birchak theory such as, information about the structure, should be considered to provide a better representation of the link between magnetic and magnetomechanical characteristics of an alloy.

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