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Static deformation of a ferromagnet in alternating magnetic field

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ABSTRACT

Static deformation of a ferromagnet under an action of ac magnetic field was observed and investigated in this work. The effect is due to even and nonlinear dependence of magnetostriction on magnetic field. It is shown that the deformation is proportional to the second derivative of magnetostriction over the field at low fields and depends on the static bias field. The deformation grows nearly linearly and then saturates with increasing ac field. For the samples with very different parameters like permendur and nickel the ac field induced static strain can reach ~50% of the saturation magnetostriction.

1. Introduction

The phenomenon of magnetostriction (change of linear dimensions of a ferromagnet under external magnetic field) [1,2], is widely used at present for the fabrication of various transducers and actuators [3,4], magnetic field sensors [5], and magnetostrictive motors [6]. Ferromagnetic materials used in such devices provide magnetostrictive strain from $\sim 10^{-6}$ ($=1$ ppm) (for example, Fe) up to $\sim 10^{-3}$ ($=10^3$ ppm) (alloys $TbFe_2$, $SmFe_2$, and Terfenol-D). Some ferromagnets extend, for example Co, while the others, for example Ni, contract under an action of the field. Control of magnetostrictive devices is carried out by permanent or slowly varying magnetic fields. Therefore, an important problem is to study specific features of ferromagnets' deformation under an action of ac magnetic fields, which is the subject of the present research.

Fig. 1 shows typical magnetic field dependence of the relative deformation $S(H) = \lambda(H) = \Delta l/l$ for a ferromagnetic sample of the length l along the direction of permanent magnetic field H. It is seen that the dependence is nonlinear and the magnetostriction saturates at the level λ_S under the fields $H > H_S$. The strain keeps its value and sign as the field direction is reversed. It follows from the shape of the curve that the character of the ferromagnet's deformation under an action of the ac field $h(t)$ with frequency f depends on the bias field H_0 as well. For the field $H_0 \neq 0$ and low amplitude of ac field $h < < H_0$, a periodic strain $s(t)$ with frequency f arises in the sample, in addition to the static deformation $\lambda(H_0)$. If the static bias field is absent, $H_0 = 0$, then the unidirectional ac strain $S(t)$ at double frequency $2f$ is generated (see Fig. 1). This deformation can be represented as a sum of the static strain S_0 and a set of harmonic strains with frequencies $2f$, $4f$ and so on. It follows that a nonlinearity of magnetostriction under action of ac magnetic field results in an appearance of additional static deformation of the ferromagnetic sample.

The present paper provides a simple theory of the effect at low amplitudes of ac magnetic field, reports relevant experimental results, and presents a method allowing calculation of static deformations of a ferromagnet for arbitrary magnetic field strength.

2. Theory

Let us take a ferromagnetic sample in the shape of a rod or a plate placed in the longitudinal ac magnetic field $H(t) = H_0 + h(t)$, where $h < < H_0$. Consider a one-dimensional problem. Variations of the sample dimensions in transverse directions caused by the magnetostriction will be neglected. Fields will be assumed to be homogeneous. After expanding the magnetostriction as a Taylor series in the vicinity of H_0, we get

$$\lambda(H) = \lambda(H_0) + qh + (1/2)ph^2 + \ldots, \quad (1)$$

where $q = (\partial\lambda/\partial H)|_{H_0}$ and $p = (\partial^2\lambda/\partial H^2)\big|_{H_0}$ are the first and the second derivatives of λ with respect to the field at $H = H_0$, respectively. In Eq. (1) q is the piezomagnetic coefficient and p is the nonlinear piezomagnetic coefficient. After substituting the harmonic field $h(t) = h\cos(2\pi ft)$ in Eq. (1) and regrouping the terms, we get the expression for the strain [7]:

$$S = \lambda(H_0) + (1/4)ph^2 + qh\cos(2\pi ft) + (1/4)ph^2\cos(4\pi ft). \quad (2)$$

The first term in Eq. (2) $\lambda(H_0)$ is the static deformation of the

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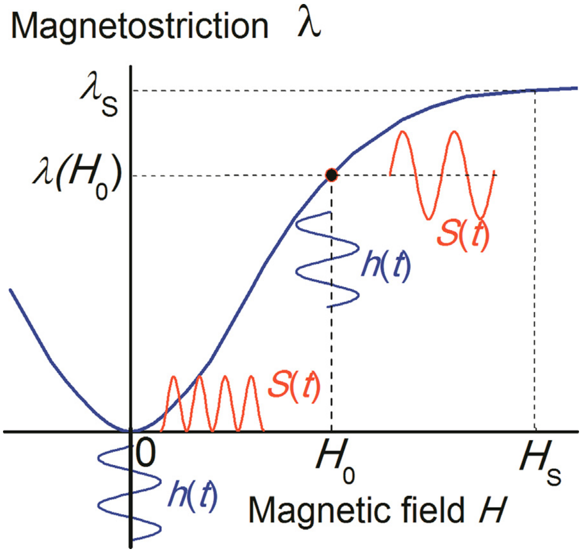

Fig. 1. The magnetostrictive strain λ of a ferromagnet as a function of magnetic field H. H_0 is a permanent bias field, $h(t)$ is the ac magnetic field, $S(t)$ is the ac strain.

ferromagnet in dc field, it vanishes for $H_0=0$. The second term in Eq. (2) $S_0=(1/4)ph^2$ describes additional static strain generated in the ferromagnet under ac magnetic field. The ac components $qh\cos(2\pi ft)$ and $(1/4)ph^2\cos(4\pi ft)$ of the strain correspond to excitation of acoustic oscillations with frequencies f and $2f$ in the ferromagnet, respectively.

It follows from Eq. (2) that static strain in the ferromagnet s_0 in a weak ac magnetic field h is proportional to the nonlinear piezomagnetic coefficient p and magnetic field squared h^2. On can see from Fig. 1 that the coefficient p is a function of H_0. Therefore, the additional deformation s_0 should depend on the field H_0 as well.

3. Experimental results

In the experiment we used ferromagnetic materials having different values and signs of magnetostriction and different saturation fields: a plate of permendur $Fe_{0.49}Co_{0.49}V_{0.02}$ (FeCo) with the dimensions of 20 mm × 10 mm × 0.4 mm and a plate of pure nickel (Ni) with the same dimensions. The samples were placed in between the poles of an electromagnet in the tangential dc magnetic field H_0 up to 2 kOe directed along the long side of the sample. The ac magnetic field $h\cos(2\pi ft)$ with amplitude of up to 560 Oe and frequency $f=50$ Hz was produced by the Helmholtz coils and directed along the dc field. Static deformation of the sample was measured using a strain gauge glued on the sample surface. The dc component of the signal was acquired with a low-frequency pass-band filter. The field was measured with an accuracy of 1 Oe and the strain was measured with an accuracy of 0.5 ppm.

Fig. 2 shows the effect of ac field $h=200$ Oe on the shape of static strain vs. magnetic field dependence for the FeCo sample. In the absence of ac field ($h=0$) the magnetostriction of FeCo reaches the saturation level $\lambda_s\approx 63$ ppm in the fields H_s ~2 kOe. After turning on the ac field and $H_0=0$, the sample extends and the ac field induced static strain reaches $S_0\approx 12$ ppm. The ac field does not affect the static strain in the sample for $H_0\approx 250$ Oe. In the fields $H_0>250$ Oe the sample undergoes an additional contraction under action of ac field. In the fields $H_0>H_S$, when the sample is saturated, the ac magnetic field does affect the static strain in the sample.

Fig. 3 shows the influence of ac magnetic field $h=85$ Oe on the static deformation of the Ni sample. In the absence of ac field ($h=0$) the saturation magnetostriction of Ni reaches $\lambda_s\approx -30$ ppm at saturation field H_S ~0.7 kOe. After turning on the ac field and $H_0=0$, the sample contracts. The ac field does not affect the static strain in the sample for $H_0\approx 70$ Oe. In the fields $H_0>70$ Oe the sample undergoes additional contraction under action of the ac field. In the fields higher than the saturation fields for Ni, the ac field does not affect the static strain in the sample.

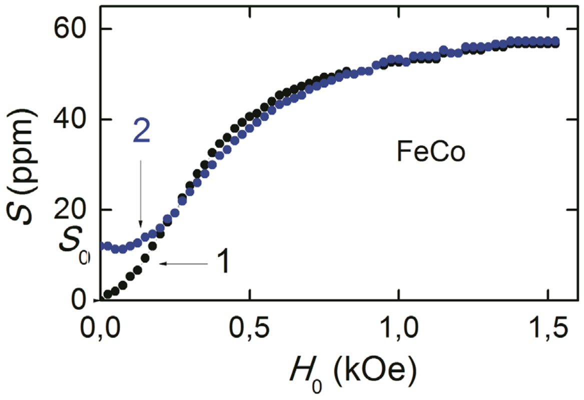

Fig. 2. Static deformation of FeCo plate S as a function of dc magnetic field H_0 for different ac fields: 1 – $h=0$, 2 – $h=200$ Oe.

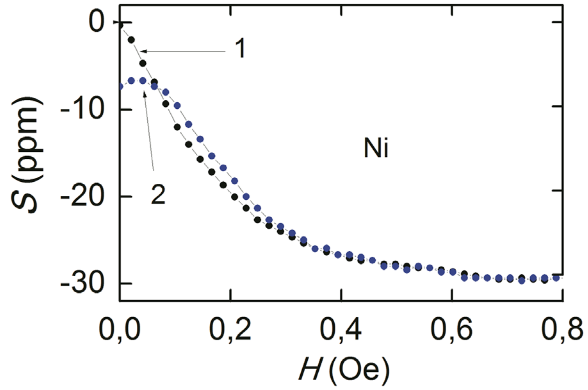

Fig. 3. Static deformation of Ni plate S as a function of permanent magnetic field H_0 for different ac fields: 1 – $h=0$, 2 – $h=85$ Oe.

Figs. 4 and 5 show dependences of static strain S_0 conditioned solely by the ac field on the field H_0 for the FeCo and Ni samples. The dependences have been obtained by subtracting the curves $S_0(H_0)=S(h, H_0)-S(h=0, H_0)$, shown in Figs. 2 and 3. For both materials the static strain S_0 has a maximum without bias field, at $H_0=0$. The deformation changes the sign as H_0 is increased and

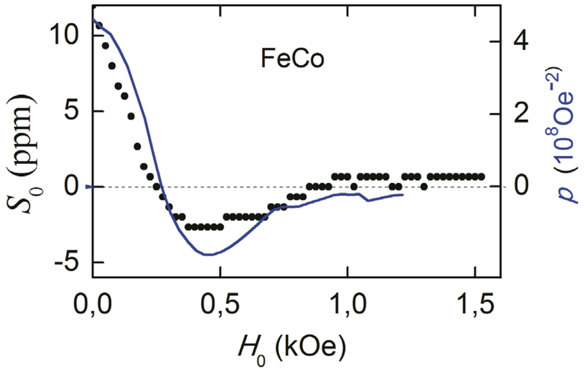

Fig. 4. Dependence of the static strain S_0 induced by ac magnetic field $h=200$ Oe in the FeCo plate on dc bias magnetic field H_0. Solid curve is calculated field dependence of nonlinear piezomagnetic coefficient $p(H_0)$ for FeCo.