Journal of ELECTRICAL ENGINEERING, VOL 63. NO 7s, 2012, 9-14

MAGNETOSTRICTION MEASUREMENTS ON SOFT MAGNETIC RIBBONS

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Different experimental possibilities to measure the magnetostriction are discussed. Special emphasis is laid on the measurement of the magnetostriction of ribbon shaped samples. For this purpose crystalline $Fe_{85}Ga_{15}$ ribbons, an amorphous $Fe_{66}Co_{18}Si_1B_{15}$ sample and a crystalline $Fe_{83.5}Si_{16.5}$ ribbon were investigated at room temperature. In this work, measurements of magnetostriction using SAMR and standard strain gauge methods were performed and the results were compared. In order to investigate the influence of stress on magnetostriction of $Fe_{85}Ga_{15}$, the hysteresis loop was measured applying different stresses. The stress dependence of the coercivity shows a minimum at around 120MPa, which value corresponds to the onset of deviation from the initial coefficient $dH_{dc}/d\sigma$ in SAMR method.

Keywords: magnetostriction, strain gauge, SAMR method, ribbons

1 INTRODUCTION

Magnetostriction is the change of length applying an external magnetic field on ferromagnetic samples. It is an intrinsic property which occurs mainly due to a spin orbit coupling of the magnetic moments (spins). The order of linear magnetostriction magnitude λ ($\lambda = l\text{-}l_0/l_0$, where $l\text{-}l_0$ is the change of length with applied field) can be between 10^{-2} ppm and 10^{-3} ppm.

For materials which are interesting for sensor or actuator applications a high magnetostriction is necessary. The most famous materials is Terfenol D (Tb-$DyFe_2$) which exhibits a magnetostriction of more than 1000 ppm at room temperature [1]. However the high costs of the raw materials together with a high anisotropy of the rare earths is limiting for many applications.

A high magnetostrictive ferrite such as polycrystalline $CoFe_2O_4$ can be produced as a powder, *eg*, by a wet chemical method [2-3]. The powder is afterward compacted by pressing. The magnetostriction of pressed cobalt ferrite depends on the pressing and annealing processes [4-5]. High magnetostriction as 400 ppm can be achieved [5]. The effect of powder composites with different elastic constants also influences the measured magnetostriction value [6].

For technical applications, soft magnetic materials with high magnetostriction are of large importance. There exist new materials such as Fe-Ga alloys (Galfenol) or Fe-Al (see *eg* [7-10]) which meet these conditions. Specially, Galfenol alloys exhibit high magnetostriction with magnetically induced strain in the [100] direction as high as 400 ppm in single crystals and 250 ppm in highly textured polycrystals [11]. However, its magnetostriction value depends on annealing process of the samples and also on applied external stresses [7, 11] which influence the magnetoelastic energy ($\sim\lambda\sigma$). On the other hand the magnetoelastic energy contributes to the hysteresis loop of a ferromagnetic material besides other contributions such as magnetocrystalline anisotropy, stray field energy, *etc*. Beside the microstructure (which determines the local demagnetizing field) the interplay between the magnetocrystalline anisotropy and the magnetoelastic energy determines the magnitude of the coercivity, therefore magnetostriction and coercivity can be related. For most soft magnetic materials the magnetoelastic energy is more important than the magnetocrystalline anisotropy.

Galfenol alloys can be produced either bulk or also as thin ribbons after a rapid quenching process [12-13]. Our previous studies have revealed the influence of quenching rates on magnitude of magnetostriction of the amorphous [14] and crystalline [12] materials. In this work, we measured the magnetostriction of crystalline $Fe_{85}Ga_{15}$ and $Fe_{83.5}Si_{16.5}$ and amorphous $Fe_{66}Co_{18}Si_1B_{15}$ ribbons using SAMR (Small Angle Magnetization Rotation) and standard strain gauge methods. The sample size and the dimensions (thickness) determine the measurement method which can be used, which is best suited to study the magnetostriction for various kinds of materials.

2 MEASUREMENT METHODS

Tables 1 and Table 2 give a summary for generally used, microscopic and macroscopic methods to measure small changes in length. Within microscopic methods, we applied differential EXAF to study the magnetostriction of Fe-Ga ribbon on an atomic scale, see *eg* [15]. The advantage of this methods is that even with polycrystalline material one can obtain single crystal information [15]. The sensitivity of a diffraction experiment is limited by sample dependent line broadening effects (stress, grain size). XRD or neutrons experiments are limited for European large scale facilities such as ESRF and ILL in Grenoble.

Macroscopic methods here presented can be used for single crystals as well as for polycrystalline materials. On bulk material all three methods can be used. The simplest and fastest method is the strain gauge method. It delivers very reliable results with a sensitivity of ±1 ppm. This method can be used in a temperature range from 1.5K up.

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ISSN 1335-3632 © 2012 FEI STU

Tab. 1. Microscopic methods to measure small changes in length.

Methods	Sensitivity	Sample	External Parameters (T, H)
X-ray diffraction	10^{-5}	Bulk, powder, thin film, polycrystal	1.5 - 2000 K 0 -7 T
Neutron diffraction	10^{-5}	Bulk, powder, thin film, polycrystal	0.01 - 600 K 0 - 15 T

Tab. 2. Macroscopic methods to measure small changes in length.

Methods	Sensitivity	Sample	External Parameters (T, H)
Capacitive Dilatometry	10^{-8}	Bulk, single and polycrystals	0.01-1000 K 0 - 50 T
Strain Gauge	10^{-6}	Bulk, single and polycrystals	1.5 - 500 K 0 - 30 T
Interferometry	10^{-8}	Bulk, single and polycrystals	4 - 2000 K 0 - 40 T
SAMR	10^{-8}	Amorphous and crystalline ribbons and wires	4 - 700 K 0-100 kA/m

to about 500K. The upper temperature is limited by the technology of the strain gauge as well as the glue. With strain gauges dynamic magnetostriction (applying a pulse or an ac-field) can also be measured. At low temperatures, for applied field larger than 15 T, a problem starts to occur. The magnetosresistance of strain gauges increasing with the square of the applied field, causing large measurement errors. The strain gauge method can be also used to measure the magnetostriction of a ribbon; however gluing the gauge on a thin sample can introduce additional stress influencing the real value of the magnetostriction of the material. Additionally the sample with gauge must be well fixed to avoid any bending effects causing strong scattering values [16].

For amorphous ribbon or wire shaped samples the well known SAMR (Small Angle Magnetization Rotation) method can be used [17]. In the case of crystalline materials like Fe-Si and Galfenol thin ribbons can be produced. The measurement of the magnetostriction in thin ribbons with strain gauges is difficult and sometimes deliver wrong results due to bowing effects [16]. The effect of gluing can cause induced stress on the sample surface which results in deviations from the true value of the magnetostriction. The accurate measurement of the magnetostriction of ribbons and thin films is a serious and difficult problem. However the SAMR and strain gauge methods represent a simple way to obtain magnetostriction on ribbons.

3 SAMR VERSUS STRAIN GAUGE METHOD

3.1 SAMR method

In 1980 the small angle magnetization rotation (SAMR) method was first reported by Narita et al. [17]. It is based on the fact that the magnetization M_s of a magnetostrictive ribbon, simultaneous saturated longitudinally with a static field H_{dc} under a tensile stress σ, rotates a small angle θ out of the axial direction when a transverse drive field H_{ac} is applied (Fig. 1). When H_{ac} has a constant amplitude and frequency, it is possible to measure the saturation magnetostriction λ_s indirectly by adjusting H_{dc} under certain stress for a constant induced voltage $V_{2\omega}$ in a pick up coil around the ribbon, which is equivalent to a constant angle θ:

$$\lambda_s = -\frac{\mu_0 M_s}{3}\left|\frac{dH_{dc}}{d\sigma}\right|_{V_{2w}H_{ac}} \tag{1}$$

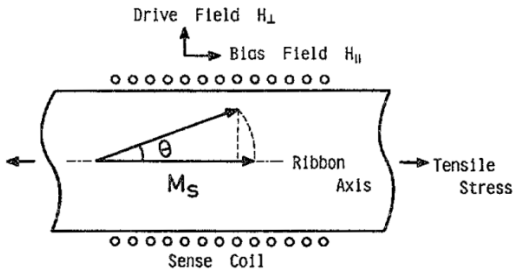

Fig. 1. Schematic presentation of SAMR in ribbon plane [17]

In this case it has been not only assumed that θ is very small, which is possible because of the small amplitude of the applied ac field, but also that the magnetization rotates uniformly throughout the specimen inside the pick up coil.

Hernando et al. pointed out that the sensitivity of this method decreases with the square of the saturating field, which becomes a problem in measuring high magnetostrictive amorphous samples [19]. The local anisotropy originating from internal stresses (due to the quenching process) via magnetoelastic coupling requires stronger fields for saturation. Therefore the sensitivity decreases with the square of the magnetostriction of the sample [19].

3.2 Strain gauges

On the other side the resolution of magnetostriction measurements via strain gauges is field independent with a reference strain gauge used to compensate the magnetoresistance. In the present work the magnetostriction was measured in a pulsed field system (pulse duration 50ms, maximum field 5T) using a fast 50 kHz strain gauge bridge (Hottinger model KWS 3085 A). However there exist also mechanical limits (thickness

of the ribbon relatively to the strain gauge, local stress) as well as the properties of the glue between sample and strain gauge which have to be considered. Generally the strain gauge method is less sensitive than SAMR. Also bowing, bending and torque effects can occur when measuring thin samples, which can lead to wrong results [16].

Applying the strain gauge method for polycrystalline material, it is recommend to perform the measurement of λ_{long} which is the magnetostriction measured longitudinal and λ_{trans} transversal to the applied magnetic field to characterize a polycrystalline material completely (volume magnetostriction, texture, *etc*).

In a cubic, isotropic material, having domains initially oriented randomly, the relation

$$\lambda = \frac{3}{2}\lambda_s\left(\cos^2\theta - \frac{1}{3}\right) \tag{2}$$

is applicable if the average of $\cos^2\theta$ over all domains is used. Here θ is the angle between the direction of field and the direction in which the change in length is measured. The constant λ_s can be determined in any magnetic polycrystalline material by measuring λ in a saturating applied field first parallel (λ_{long}) and then at an angle perpendicular to the direction of external field (λ_{trans}). The total change in length caused by the change in field, known also as shape magnetostriction, is then given by

$$\lambda_{total} = \lambda_{long} - \lambda_{trans} = \frac{3}{2}\lambda_s \tag{3}$$

independent of the initial domain distribution. When the change in length is measured at $\theta = 90°$, in the magnetically saturated state of a polycrystalline isotropic material one expects to obtain

$$\lambda_{trans} = -\lambda_{long}/2 = -\lambda_s/2 \tag{4}$$

4 RESULTS AND DISCUSSIONS

For comparing the achievable results between SAMR and strain gauges three different types of samples have been chosen - a high magnetostrictive amorphous ribbon, $Fe_{66}Co_{18}Si_1B_{15}$ (d = 23 μm) and two crystalline ribbons with high, $Fe_{85}Ga_{15}$, (d = 45 μm), and low magnetstriction, $Fe_{83.5}Si_{16.5}$. (d = 37 μm) - where d corresponds to the thickness of the ribbons.

Fig. 2 shows, despite the high magnetostriction, a good result of the SAMR measurement due to the fact that the amorphous $Fe_{66}Co_{18}Si_1B_{15}$ ribbon is really a soft magnetic material, where the saturation is reached in a rather low field compared to the other samples investigated here. Fig. 3 shows longitudinal and transverse magnetostrictions measured with strain gauges. The results of SAMR should be comparable with that of the strain gauge longitudinal to the ribbon axis, because the tensile stress in SAMR is also applied in the same direction (see Fig. 1). However, we found λ_{long} (35 ppm) smaller than λ_S obtained from the SAMR method (41.7 ppm). Local stresses (due to quenching rate and glue) of the ribbon can have a strong influence on the strain gauge measurement, since they are the source of local anisotropy via magnetoelastic interaction. In fact, one can see that the relation (4) is not fulfilled here.

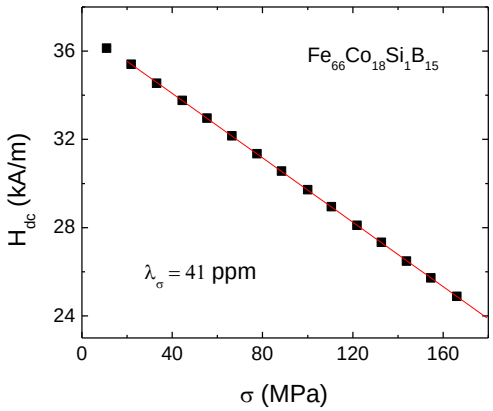

Fig. 2. SAMR measurements at room temperature of $Fe_{66}Co_{18}Si_1B_{15}$

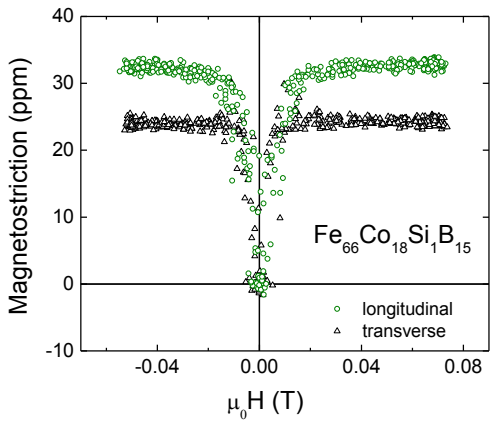

Fig. 3. Strain gauge measurements at room temperature of $Fe_{66}Co_{18}Si_1B_{15}$

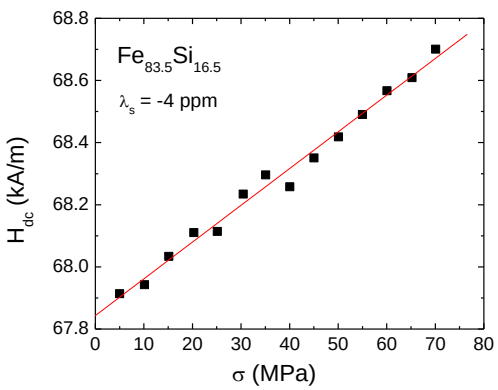

Fig. 4. Magnetostriction of $Fe_{83.5}Si_{16.5}$ measured by SAMR method

In the case of a crystalline $Fe_{83.5}Si_{16.5}$ ribbon (see Fig. 4 and Fig. 5 measured by means of SAMR and strain

gauge, respectively), the limits of both measuring methods are reached. Although the sample is wavy, which makes the SAMR measurement a difficult task; nevertheless both measurements show similar results for λ_{long} and λ_s.

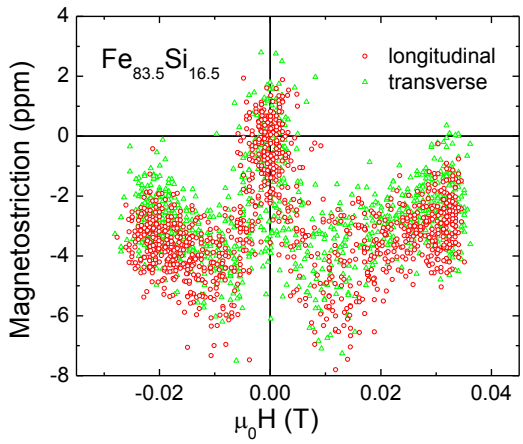

Fig. 5. Strain gauge measurements of $Fe_{83.5}Si_{16.5}$.

The strain gauge measurement of crystalline $Fe_{85}Ga_{15}$ ribbon is shown in Fig. 6. Surprising in this sample the validity of relation (4) is observed, indicating that the sample is isotropic, which may be due to the fact that the material is nanocrystalline. The X-ray Rietveld analysis of the Fe-Ga ribbon gave a small grain size of around 150nm, which should be suitable for a mean value in the strain gauge measurement and also lead to an acceptable SAMR result. In this case the longitudinal magnetostriction can be compared with the saturation mangnetostriction determined by SAMR measurements.

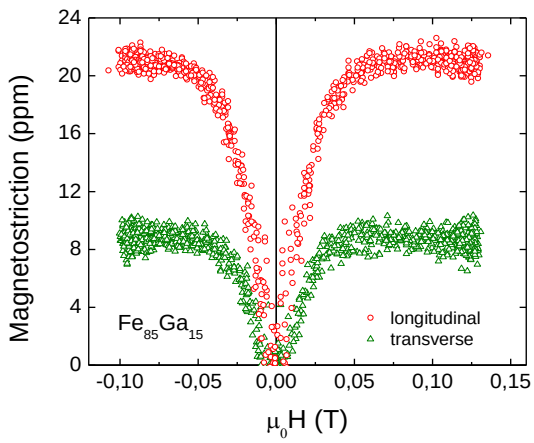

Fig. 6. Strain gauge measurements of $Fe_{85}Ga_{15}$.

Fig. 7 shows the SAMR measurements performed on a similar $Fe_{85}Ga_{15}$ ribbon for different applied static fields. It shows the expected problematic case of a rather high field which is necessary to saturate the sample, and also the influence of internal and external [20] stress on the measurement. After overcoming the internal stresses and applying a sufficient high static field, H_{dc} > 70 kA/m, reasonable magnetostriction results could be obtained, although the sensitivity decreases [19]. The magnetoelastic energy (stress $\sigma \times$ magnetostriction λ) leads in such a material to a magnetostriction (also permeability, modulus) that varies with stress (internal and external) and field. From these measurements, we obtain a saturation magnetostriction of about 21 ppm, which is practically the same as that found by the strain gauge method that which is about 22 ppm. Previous works have revealed a large influence of quenching rates and the existence of texture on magnetostriction values of both bulk [8] and ribbon [12] samples, therefore the strong field and stress dependence of the SAMR results may be explained by these factors.

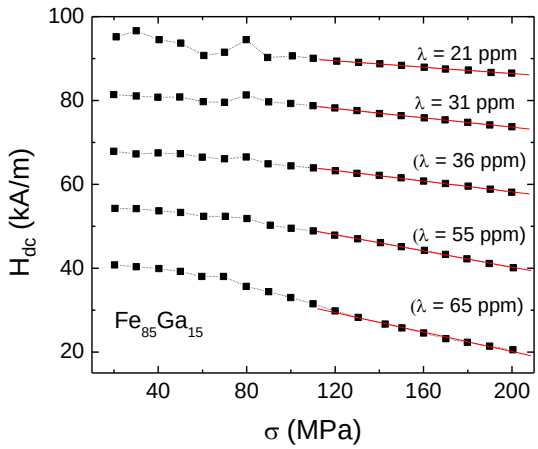

Fig. 7. SAMR measurements measure at room temperature of $Fe_{85}Ga_{15}$.

In order to determine at which applied field the material is approximately saturated and to investigate the influence of applied stress on coercivity, a hysteresis measurement on the same ribbon was performed at room temperature. One example of these measurements is shown in Fig. 8. One can see that the field range necessary for SAMR method must be at an external field H_{dc} > 60kA/m.

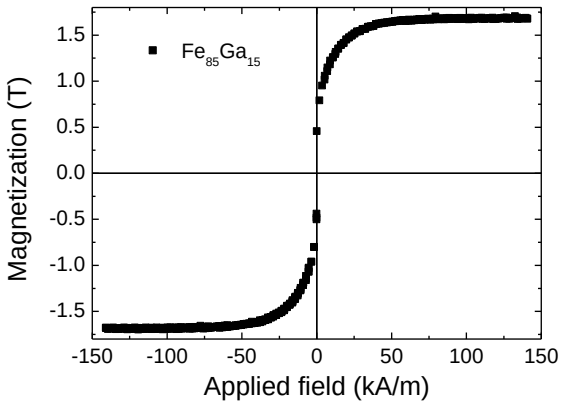

Fig. 8. Room temperature hysteresis measurement performed on a $Fe_{85}Ga_{15}$ ribbon.

The effect of internal stress is well visible in the stress dependence of the coercivity (see Fig. 8), which presents a minimum at about 120 MPa which corresponds to the kink in the SAMR measurements (see Fig.7). This minimum in the $H_c(\sigma)$ curve indicates that the internal stresses, due to

the quenching process were recompensated by applying external stress.

Since the internal stresses are the main source of anisotropy, the parameter *b* (that is related directly to the magnetic anisotropy *K*) of the well known law of approach to the magnetization saturation,

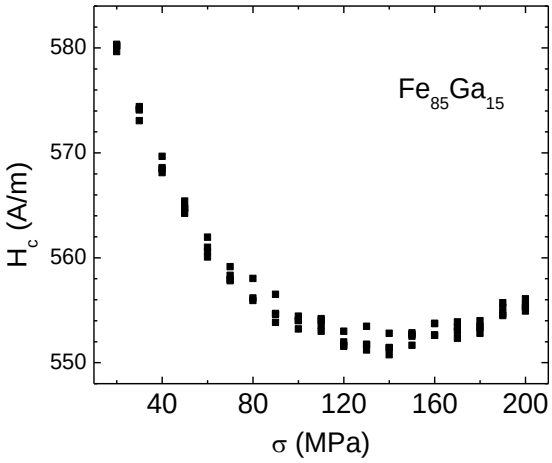

Fig. 9. Stress dependence of the coercivity measured at room temperature on a ribbon of $Fe_{85}Ga_{15}$.

$$M = M_s(1 - b/H^2)$$

was determined for different applied stresses, where *H* is the applied field and

$$b = \frac{8K^2}{105(\mu_0 M_S)^2} + \frac{3\lambda_S^2\langle\sigma^2\rangle}{5(\mu_0 M_S)^2} \tag{5}$$

for randomly oriented polycrystalline samples with a cubic crystal structure. In fact, Fig. 10 shows the coefficient *b* which initially decreased up to *P* = 120 MPa and later increased with increasing stress. As expected regarding equ. 5, *b* vs. applied stress behaves similar to H_c *vs.* σ shown in Fig. 9.

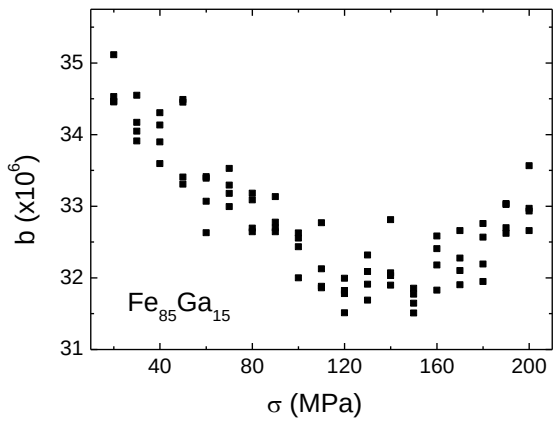

Fig. 10. Stress dependence of the coefficient *b* determined from room temperature hysteresis measurements on a ribbon of $Fe_{85}Ga_{15}$.

From these results it is confirmed that the magnetostriction, anisotropy and coercive field values in $Fe_{85}Ga_{15}$ are undoubtedly affected by the internal and applied stresses, although additionally one should consider also the influence of the microstructure.

5 CONCLUSIONS

The following conclusions were achieved for thin ribbons (amorphous or microcrystalline): It has been shown that within the requirements of the SAMR method, which are a small angle displacement of the magnetization and a saturated state of the sample due to a sufficient high longitudinal field, it is possible to receive accurate measurement results not only for high magnetostrictive amorphous materials, but also for crystalline ribbons, although the sensitivity decreases for higher saturation fields and the internal stress has to be overcome first. Thus good mechanical properties are very important to apply homogeneously distributed tensile stress and a small grain size of the polycrystalline material is needed to receive a comparable mean value between the indirectly measured saturation magnetostriction by induced signal of SAMR and the local and direct measuring method of the strain gauge. However local internal stresses and possible bowing effects can still lead to scattering results in measuring with strain gauges on ribbons. For crystalline bulk sheets with thicknesses above 0.1mm (as typical for Fe-Si sheets) the strain gauge method is most reliable and easy to handle. The sensitivity of this method is limited to about 1 ppm. An easy applicable and reliable measuring system suitable for thin ribbons (and films) is still missing.

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Received 8 September 2012

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