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Joulian magnetostriction of Galfenol $Fe_{83}Ga_{17}$

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ABSTRACT

The volume change on magnetic saturation of a large single crystal of $Fe_{83}Ga_{17}$ is measured by Joule's liquid displacement method. The crystal was tested in the as-grown state, and after annealing at 760 °C followed by slow cooling at 10 °C/min or quenching in water. In each case an upper limit to any volume change is < 5 ppm, establishing that the linear magnetostriction is volume-conserving. The conclusion agrees with that drawn from a study of a dozen small crystals of Fe–Ga by the strain gauge method, but the demonstration of volume conservation using Joule's original method is more direct.

1. Introduction

Shortly after Joule discovered the linear magnetostriction of iron in 1842 [1], he conducted an experiment where he immersed an iron bar in water and measured the change of liquid level in a capillary when the bar was magnetized to saturation [2]. His conclusion was that the volume of the iron was conserved, and that the expansion $\lambda_{||}$ in the direction of the applied field was offset by compensating contractions $\lambda_{\perp} = -\frac{1}{2}\lambda_{||}$ in the perpendicular directions. This volume-conserving linear magnetostriction, known ever since as Joulian magnetostriction, is the normal magnetoelastic response of ferromagnetic metals and alloys. A forced volume magnetostriction ω may also appear in high fields, after saturation, but the effect is normally very small [3].

Linear (i.e. directional) saturation magnetostriction in an intrinsic tensor property of a crystal; just two constants λ_{100} and λ_{111} suffice to describe the effect in cubic symmetry. Although magnetostriction refers to the magnetically-saturated state where the domain structure has been eliminated, in practice it is always the *difference* in strain between an initial unmagnetized multidomain state and the final saturated state that is measured [3]. If the domains are initially isotropically distributed, as they were in Joule's large polycrystalline iron rod, then the changes in strain in the directions parallel and perpendicular to the applied field are $\lambda_{||}$ and $-\frac{1}{2}\lambda_{||}$. If we have a single crystal rod orientated along a cube edge, [1 0 0] for example, which is an easy direction of magnetization, and in its initial state the domains are distributed with their magnetization equally along the six ⟨1 0 0⟩ directions as shown in Fig. 1(a), then the saturation magnetostriction $\lambda_{||} = \lambda_{100}$, the magnetostriction constant of the material. However, a different domain structure in the demagnetized state can produce quite different results. For instance, if the domains were initially aligned with the long, z axis of the sample, as shown in Fig. 1(b), there will be no change in strain in any direction on saturation in a field applied along the z-axis, but in a field applied along the x-axis, the changes of strain in strain in the x, y, and z directions are $(3/2)\lambda_{100}$, 0 and $-(3/2)\lambda_{100}$, respectively. But in any case $\Sigma\lambda_i = 0$, where the sum is of the saturation magnetostriction in a given applied field measured in three orthogonal directions. This condition is the test for Joulian magnetostriction.

Chopra and Wuttig have published a paper claiming giant non-Joulian magnetostriction in highly magnetostrictive Fe–Ga crystals [4]. The original report did not contain any measurement of λ_i in three orthogonal directions, but in an addendum [5] strain gauge data on one of their thin crystals was shown, where $\lambda_{[110]} + \lambda_{[-110]} + \lambda_{[001]} = 134$ ppm, in support of their original claim. A crystal of similar composition exhibited an unusual surface domain structure.

Here we investigate the magnetostriction of $Fe_{83}Ga_{17}$ (Galfenol) to ascertain whether or not the giant magnetostriction of this important functional material [6] is normally non-Joulian.

2. Experimental procedure

A large single crystal (Fig. 2(a)) was grown by the Bridgeman method at a rate of 25 mm/h. The crystal had a diameter of 16 mm and a length of 70 mm, giving a volume of 14,073 mm^3. The long axis was in a [0 0 1] direction. The demagnetizing factor of the cylinder [7] was $\mathcal{N} = 0.092$, and the magnetization was $M = 1.38$ MAm^{-1}. The longitudinal magnetostriction, measured with a strain gauge was $\lambda_{[001]} = 176$ ppm. The crystal was measured in three different conditions by Joule's method. First was in the as-grown state. Then the crystal was annealed for 30 min at 760 °C and quenched in water, and finally it was reannealed for 30 min at 760 °C and slowly cooled at 10 °C per minute.

The experimental setup is illustrated in Fig. 2(b) and (c). The crystal was placed in a flat-bottomed 250 mL flask filled with alcohol, and stoppered with a rubber bung including a 0.3 mm diameter capillary tube. Care was taken to avoid bubbles, and the setup was tested by warming the flask slightly by hand and observing the rise in the alcohol level in the capillary. The flask was placed between the poles of an electromagnet capable of generating a field of 200 mT, which is sufficient to saturate the rod, since $\mu_0\mathcal{N}M_s = 159$ mT. A change of alcohol level of 1 mm in the capillary would be easily observable, corresponding to a volume change of the crystal of 5 ppm.

3. Results and dicussion

Results are simply stated: No change was observed in the alcohol level for any of the three conditions of the crystal. In every case the

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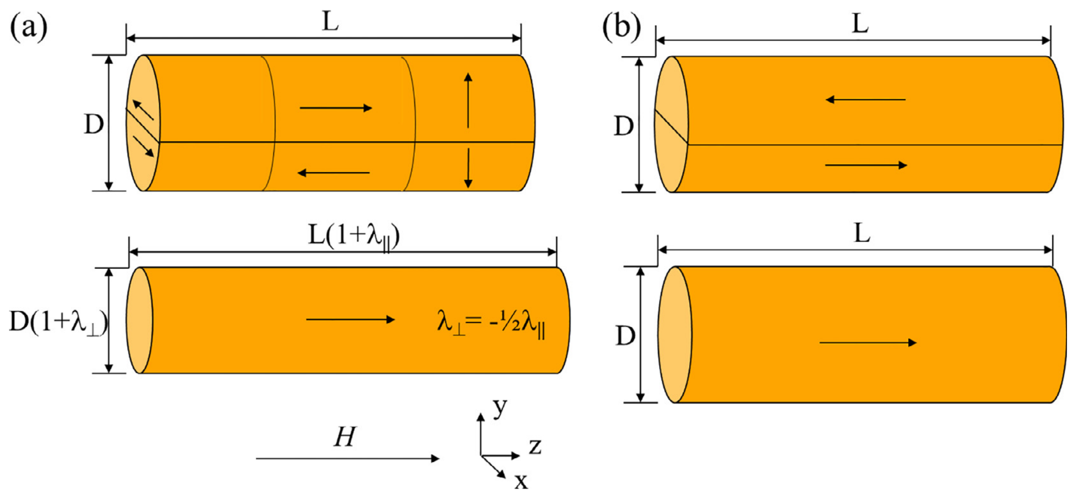

Fig. 1. Magnetostrictive deformation of (a) a cubic crystal with an isotropic initial domain state, and b) the same crystal with an initial state where the domains are magnetized along [0 0 1], and the magnetization process involves 180° domain wall motion. There is no change of magnetostrictive strain on saturation in (b), but in both cases the magnetostriction is Joulian and $\Sigma\lambda_i = 0$.

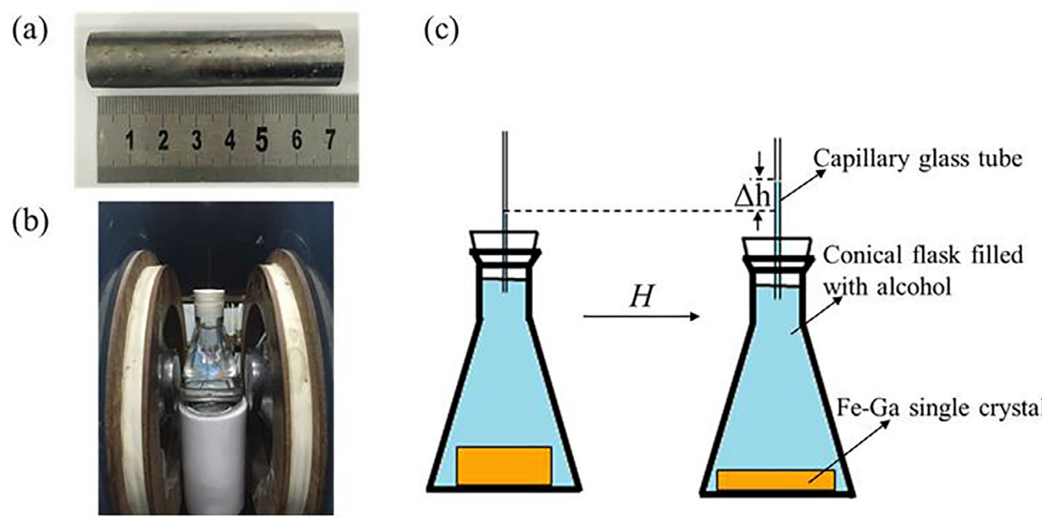

Fig. 2. (a) A photograph of the $Fe_{83}Ga_{17}$ crystal used in the liquid-displacement experiment. (b) a photograph of the setup and (c) a schematic drawing.

volume change was less than 5 ppm. The magnetostriction was always Joulian.

We have also examined a dozen small crystals of $Fe_{83}Ga_{13}$ or $Fe_{74}Ga_{26}$, observing their domain structure and measuring $\Sigma\lambda_i$ in 31 different cases. Details are reported elsewhere [8,9]. Results for the sum ranged from −11 ppm to 21 ppm with an average of 6 ± 7 ppm, where ± 7 is the error on the mean. Variations from measurement to measurement are attributed to small uncertainties in identifying the saturation magnetostriction when the curve is not quite flat, and errors arising when the width of the domains in the initial state approaches the active length of the gauge. The samples exhibited zig-zag domains ~ 40 μm wide with 90° domain walls that relieve magnetostrictive stress in Fe–Ga, as described by other authors [10–12], or bar domains in the thinnest crystals. None of the crystals exhibited evidence of the giant non-Joulian magnetostriction shown by Chopra and Wuttig's crystal, where $\Sigma\lambda_i$ was 134 ppm, with an error of only a few ppm.

4. Summary

In conclusion, our large $Fe_{83}Ga_{17}$ single crystal exhibits Joulian magnetostriction when measured following Joule's original method, no matter how we heat treat it. Joule's method avoids the uncertainties associated with strain gauge measurements of the response in three orthogonal directions that are associated with surface sensitivity, domain coverage and definition of saturation.

Acknowledgments

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