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"Giant" ΔE effect in amorphous alloys with perpendicular magnetic anisotropy

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Abstract

In amorphous Fe–B–P alloys we have observed the appearance of a non-monotonic dependence of the ΔE effect on magnetic field after annealing at temperatures above 300 °C. The results obtained show that this behaviour of the ΔE effect is due to a thermostimulated magnetic anisotropy perpendicular to the ribbon plane. It has been observed that after removing the near-surface layer by chemical etching, if the depth of the removed layer is greater than a certain value, the ΔE effect behaviour becomes time dependent. It is proposed that the induced magnetic anisotropy and the unusual behaviour of the ΔE effect are caused by a change in the chemical composition of the near-surface layer during heat treatment.

1. Introduction

It is well known that in some amorphous ferromagnetic material a "giant" ΔE effect has been observed [1, 2]. (The ΔE effect is the relative change in the Young modulus E caused by material magnetization. Thus $\Delta E/E(H)=[E_s-E(H)]/E(H)$, where E_s is the modulus in the state of magnetic saturation and E is the modulus at a given magnetization.) The highest values of the ΔE effect are observed in amorphous ferromagnetic ribbons with an induced transverse magnetic anisotropy. In this case the magnetic domain structure consists predominantly of 180° domains with magnetic moments oriented in the ribbon plane perpendicular to the applied magnetic field and mechanical stress, and the change in the magnetization of such a structure occurs owing to magnetic moment rotation. This type of magnetic anisotropy is usually obtained by annealing the ribbon in a transverse magnetic field or under longitudinal mechanical stresses. A very remarkable peculiarity of the "giant" ΔE effect observed in a material with an induced transverse magnetic anisotropy is that it depends strongly non-monotonically on the magnitude of the magnetic field applied.

In this paper the results of a ΔE effect investigation on amorphous Fe–B–P alloys are discussed. These materials exhibit a strong non-monotonic $\Delta E/E(H)$ dependence after being subjected only to a simple annealing without using a magnetic field or mechanical stresses to obtain induced magnetic anisotropy.

2. Experimental details

The measurements were carried out on specimens of the amorphous alloys $Fe_{83}B_{10}P_7$, $Fe_{80}B_4P_9$ and $Fe_{83}B_7P_{10}$. The heat treatment of specimens was carried out by annealing at various temperatures in a special furnace with a bifilar winding coil in an argon atmosphere or in air. The measurements of the ΔE effect were performed by a magneto-inductive technique [3] at frequencies from 100 to 200 kHz. Rectangular ($10\times2\times0.025$ mm^3) and ring-shaped (with internal and external diameters of about 6 and 12 mm respectively) specimens were used. For the rectangular specimens the external magnetic field was applied parallel to the long axis of the specimen. The ring-shaped specimens were inserted into a special cassette with winding toroidal coils that created a magnetic field directed along the circumference of the specimen. The dynamic magnetization (B–H) curve was measured in the ring-shaped specimens only.

3. Results and discussion

In Fig. 1 the dependences of the ΔE effect on magnetic field are shown for an $Fe_{83}B_{10}P_7$ specimen after 1 h annealings at various temperatures. One can see that in the case of the as-quenched state the $\Delta E/E(H)$ dependence is monotonic. Annealing at temperatures below 300 °C leads to an increase in the value of the ΔE effect and the $\Delta E/E(H)$ dependence remains monotonic. Such behaviour of the ΔE effect under heat

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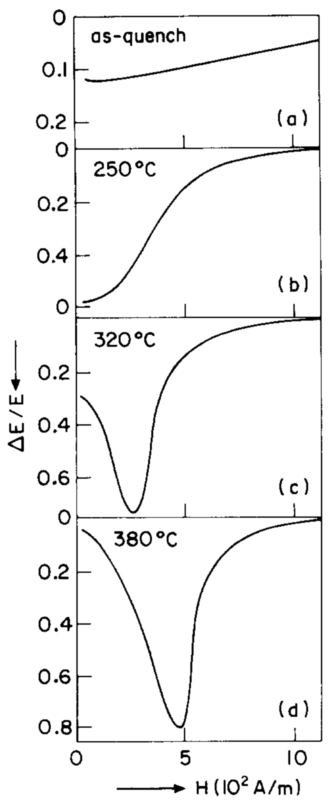

Fig. 1. Dependences of $\Delta E/E$ on magnetic field for $Fe_{83}B_{10}P_7$ specimen in as-quenched state and after 1 h annealings in argon atmosphere at various temperatures.

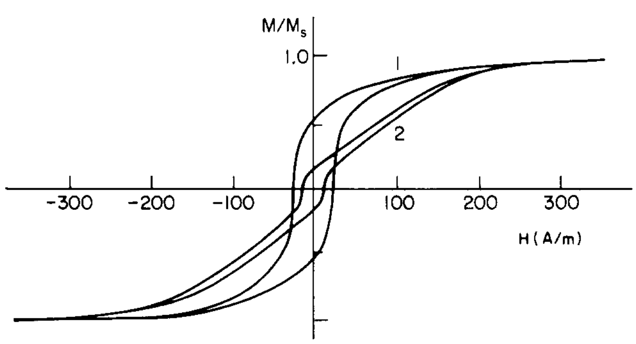

Fig. 2. Dynamic magnetization loops of $Fe_{83}B_7P_{10}$ alloy in as-quenched state (1) and after 1 h annealing at 360 °C (2).

treatment without a magnetic field or mechanical stresses is typical for most ferromagnetic alloys. However, after annealing at temperatures above 300 °C, the $\Delta E/E(H)$ dependence in Fe–B–P alloys becomes non-monotonic (Figs. 1(c) and 1(d)). To obtain a similar non-monotonic dependence in other materials (*e.g.* Fe–B alloys), it is necessary to anneal the specimen in a magnetic field to induce a magnetic anisotropy in the ribbon plane perpendicular to the ribbon axis. One might think that the non-monotonic ΔE effect behaviour in Fe–B–P alloys is also due to an induced anisotropy in the ribbon plane, though no magnetic field was applied during heat treatment.

However, this suggestion on induced magnetic anisotropy arising in the ribbon plane was not confirmed. The $\Delta E/E(H)$ dependence in Fe–B–P alloys does not depend on whether the specimen long axis is parallel or perpendicular to the axis of the ribbon subjected to the heat treatment. In both cases the ΔE effect exhibits a deep minimum. The same dependence after heat treatment was observed for ring-shaped specimens. This means that there is no magnetic anisotropy in the ribbon plane. One may assume that an induced magnetic anisotropy perpendicular to the ribbon plane exists. Indeed, measurements of the dynamic magnetization (*B–H*) curve for ring-shaped specimens confirmed this suggestion (Fig. 2). For the as-quenched specimen the *B–H* curve is similar to the curve for specimens with equally probable distribution of domain moment orientation, *i.e.* there is significant hysteresis with a value of $0.05M/M_s$ of residual magnetization in zero field. The *B–H* curve of the specimen annealed at 360 °C becomes closer to the linear one and the hysteresis area decreases greatly. For ring-shaped specimens this fact indicates that a magnetic anisotropy perpendicular to the ribbon plane arises, which is in agreement with results of ref. 4.

This thermally induced perpendicular anisotropy and the corresponding ΔE effect are steady with time and usually remain unchanged after removing (by chemical or ion etching) the near-surface layer. However, if the

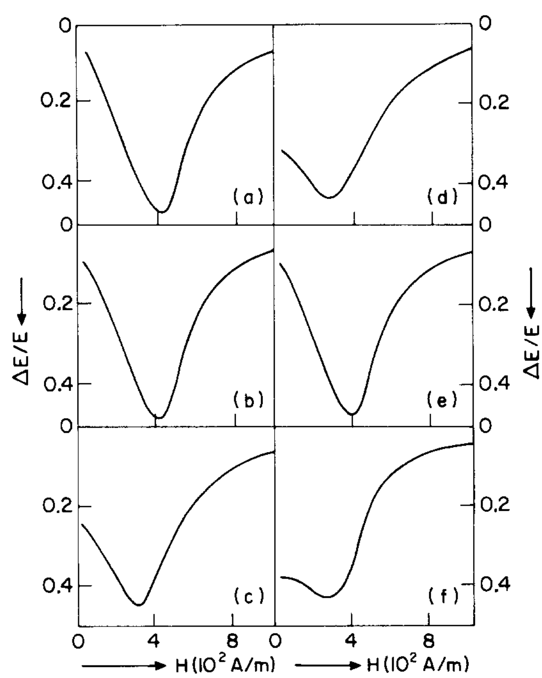

Fig. 3. Dependences of ΔE effect in Fe–B–P alloy: (a) after 1 h annealing at 360 °C in air; (b) immediately after removing 1 μm surface layer by chemical etching; (c) 3 h after etching; (d) 12 h after etching; (e) after repeated etching; (f) 24 h after repeated etching.

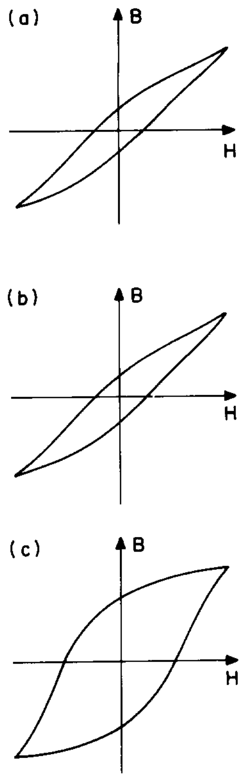

Fig. 4. Changes in dynamic magnetization loop of Fe–B–P alloy after chemical etching: (a) after 1 h annealing at 360 °C in air; (b) immediately after removing 1 μm surface layer; (c) 12 h after etching.

depth of the removed layer exceeds a certain value (for specimens annealed in air this value was about 1 μm), the ΔE effect and the dynamic magnetization curve become unstable with time (Figs. 3 and 4). They remain the same immediately after etching, but then they relax with time to a state peculiar to samples without an induced anisotropy. The characteristic time of this change is a few hours. The previous state can be restored by repeated etching (Fig. 3(e)), but in this case the ΔE effect (Fig. 3(g)) and the magnetization curve relax again. This procedure can be repeated several times. After additional heat treatment the same state arises as after previous annealing.

There are several suggestions about the nature of the perpendicular magnetic anisotropy induced in Fe–B–P alloys, though they are very hypothetical. The first is based on the known fact [4, 5] that annealings of Fe–B–P amorphous alloy lead to a ribbon surface enriched with B and P atoms in a layer less than 1 μm thick. This difference in chemical composition between the surface and the bulk of the ribbon causes compressive stresses and the appearance of a magnetic anisotropy perpendicular to the ribbon plane. The vanishing of the magnetic anisotropy after the first chemical etching could support the proposed suggestion; however, the results of repeated etchings give evidence for the existence of an induced anisotropy in the bulk of the ribbon. Thus one can conclude that this mechanism is not reasonable.

There is another suggestion. It is proposed that the diffusion of B and P atoms normal to the surface during annealing can direct the atomic directional ordering analogously to the ordering induced by magnetic annealing. However, a detailed mechanism of such an ordering is not clear yet and it is necessary to carry out structural experiments to examine how the amorphous structure of the alloy changes with annealing.

Concerning the unusual behaviour of the ΔE effect and the magnetization curve after polishing, the following mechanism can be suggested. The magnetic structure arising after heat treatment consists of 180° domains with the easy axis perpendicular to the ribbon plane and of closure domains in the near-surface layer. Owing to the presence of the near-surface layer enriched in B and P atoms the domain boundaries are fixed and the reversal of specimen magnetization occurs predominantly by the rotation of magnetic domain moments. When the chemical etching removes the near-surface layer with the closure domains, the domain structure, consisting of 180° domains only, remains and the behaviour of $B(H)$ or $\Delta E/E(H)$ is determined again by the magnetic moment rotation. However, this state is energy disadvantageous and a relaxation to the state with closure domains occurs. The formation of closure domains is accompanied by the creation of extended stresses near the surface, leading to a decrease in the magnetic anisotropy there. Then the boundaries of the closure domains become mobile and the behaviour of $B(H)$ or $\Delta E/E(H)$ is determined by the movement of these boundaries both along the surface and into the specimen. Therefore the behaviour of the ΔE effect and the magnetization curve becomes analogous to that in samples without any induced anisotropy, where the movement of domain boundaries is dominant.

This model allows us to explain qualitatively the effect of etching on the ΔE effect and the magnetization curve, though further experiments are necessary for its verification.

References

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