Magnetoelastic hysteresis of amorphous ribbons

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I. INTRODUCTION

The influence of tensile stress on hysteresis loops and the magnetomechanical effect in high-magnetostrictive Fe-rich and low-magnetostrictive Co-rich amorphous ribbons were investigated. In the as-quenched Fe-rich alloy a very complex behavior is observed, which indicates the interplay of different types of magnetization processes. Uniaxial magnetic anisotropies, induced by stress annealing, eliminate the rotational processes in Fe-rich materials and the domain-wall motion in Co-rich materials. Thus, the role of the two different mechanisms in the magnetoelastic hysteresis can be studied separately. It is shown that irreversible domain-wall movements are responsible for the large hysteresis in the Fe-rich alloy, while the purely rotational magnetization process can account for the essentially anhysteretic behavior of the Co-rich alloy. The theoretical model by Livingston [J. D. Livingston, Phys. Status Solidi 70, 591 (1982)] can well explain the anhysteretic behavior. © 2003 American Institute of Physics. [DOI: 10.1063/1.1540043]

II. EXPERIMENTAL METHODS

Two different types of material were studied. The high-magnetostrictive Fe_{65}Co_{21}B_{15} ribbon, 10 mm wide, (\lambda_s=46 \times 10^{-6}) and the low-magnetostrictive Co_{60}Fe_{21}Cr_{4}Si_{8}B_{13} ribbon, 6 mm wide, (\lambda_s=-1 \times 10^{-6}) were prepared by the planar flow casting. As-quenched and heat-treated samples were investigated. To obtain a well-defined magnetic anisotropy the ribbons were continuously stress annealed. The ribbon was moved with a constant velocity, by means of a stepper motor, through the radiation furnace with the temperature plateau about 15 cm long. The tensile stress, \sigma, was applied either by means of the weight attached to the free end of the ribbon or by unwinding the ribbon out of the bobbin, which was constrained with a constant friction.

The hysteresis loops, under applied stress, and the magnetization-stress curves were measured by means of the automated equipment schematically shown in Fig. 1. The magnetization of the sample, about 40 cm long, was measured by the standard ballistic method. The tensile stress was applied by means of the brass string, the deformation of which was controlled by the stepper motor driven via serial port of the PC. Time, magnetic field, magnetization, and stress (measured by the force gauge) were recorded for each measured point. The anhysteretic magnetic state for the given point on the (H,\sigma) plane was obtained by the mag-

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netic field oscillating around $H$ with the amplitude exponentially decaying from the initial magnitude, well above the coercive force $H_c$, to the final value of about 1% of $H_c$. To eliminate the influence of the zero drift of the flux meter during anhysteretic and the magnetization-stress curve measurements, each series of measurements started from and finished at the sample saturation. Then, the measured data were corrected for the drift, which was assumed to be linear with time, and the absolute values of magnetic polarization $J$ were calculated from the known value of saturation magnetization $J_s$.

III. EXPERIMENTAL RESULTS

The high-magnetostrictive iron-rich alloy Fe$_{64}$Co$_{21}$B$_{15}$ was investigated in the as-quenched and the stress-annealed states. Hysteresis loops, typical of soft magnetic amorphous alloys, with $H_c = 5.5$ A/m and the remanence ratio $J_r/J_s = 0.74$ are observed for the as-quenched sample. The domain structure shows the “stress pattern” typical for magnetostrictive amorphous ribbons. With applied tensile stress the remanence rapidly increases, reaching saturation at about 30 MPa. The magnetization-stress curves with the starting point lying on the unstressed major hysteresis loop were investigated. The magnetization varies with stress only for $\sigma < 30$ MPa and at higher stress $J$ remains constant with the value approximately equal to $J_s$ or to $\mu_0H/N$, depending on which value is smaller. ($N$ is the demagnetizing factor of the sample.) The magnetization changes at lower $\sigma$ are essentially reversible for fields larger than $H_c$. Irreversible changes of magnetization are observed only for the first few stress cycles at magnetic fields not much exceeding the coercive force.

To study the magnetization reversal due to only domain-wall movement the Fe-rich ribbon was continuously stress annealed at temperature 355 °C with the transport speed of 30 cm/h and the tensile stress of 129 MPa. Stress annealing of this Fe-rich amorphous alloy induces uniaxial anisotropy with the anisotropy constant $K$ about 800 J/m$^3$ and the easy axis along the stress direction. Almost regular stripe domains with 180° domain walls parallel to the ribbon axis were observed in the stress-annealed samples. The annealing temperature was chosen a bit above the crystallization temperature, which lead to partial crystallization of the material. Crystallites of $\alpha$-Fe, with the mean size ranging from 40 to 70 nm and the crystal fraction depending on the annealing time, are known to serve as pinning sites for the domain walls and increase the coercive force. The hysteresis loops of the stress-annealed ribbon (see Fig. 2) are nearly rectangular with a large slope at $H_c$. With increasing stress the coercive force decreases. The anhysteretic curve, shown by the dashed line, is stress independent and determined mainly by the demagnetizing factor of the sample. It is quite linear and its slope well satisfies the condition for zero internal magnetic field, $H_{int} = H - NM_{an} = 0$, where $M_{an}$ is the anhysteretic magnetization. The magnetization-stress curves starting from different points on the unstressed major loop are shown in Fig. 3. Only the first stress cycles are shown, for clarity, with the exception of $H = -44.7$ A/m, where the first two cycles are shown. The effect of stress on magnetization is observed mainly in the field range from $H_1$ to $H_2$ (see Fig. 2), which correspond to the upper knee on the stressed major loop and the lower knee on the unstressed major loop, respectively. Large irreversible changes (up to 100% of $J_s$) are observed on the tension branches of the first cycles. For lower applied fields or stress cycles of higher numbers the irreversible change starts at some critical stress. With increasing cycle number the critical stress increases and $\Delta J$ decreases. On the stress-release branches the magnetization is constant ("horizontal fly-back"). For some fields (especially close to the upper knee of the unstressed loop) the irreversible changes are not finished even after eight stress cycles.
With applied stress the domain structure remains, net magnetization reversal takes place only by magnetization. The domain structure consists of transversal stripe domains and the magnetic anisotropy with the easy plane perpendicular to the ribbon axis is induced. The domain-wall bowing and magnetization rotations, on the other hand, contribute to the reversible part of the magneto-mechanical effect. According to their empirical "law of approach to the principal anhysteretic," the application of stress induces such irreversible changes, which cause the magnetization to approach its equilibrium anhysteretic value.

The magnetomechanical effect in the as-quenched Fe₈₆Co₂₁B₁₅ ribbon can be qualitatively well explained by this model. The quenched-in internal stresses induce large local anisotropies with random distribution of the easy axis. At fields higher than \( H_c \) and \( \sigma < 30 \text{ MPa} \), where the magnetization rotation prevails, the magnetization change is essentially irreversible. At lower fields, where the domain-wall motion contributes, irreversible changes towards the anhysteretic curve are observed. For \( \sigma > 30 \text{ MPa} \) the quenched-in stresses are overcome by the applied stress and the domain structure is similar to that observed for the stress-annealed sample. The magnetization is stress independent and equal to the corresponding anhysteretic value.

In the stress-annealed and partially crystallized Fe-rich sample only the domain wall movements are effective. Application of stress does not produce any additional pressure on the 180° domain walls but can cause weakening of the pinning sites and irreversible movement of the walls to energetically more favorable positions. The existence of the critical stress for magnetic fields close to \( H_c \) and for higher-order stress cycles can be explained by the heavy pinning of domain walls in an array of pinning sites with a large distribution of pinning energies.² The horizontal flyback indicates that the domain walls are rigid and the contribution of the reversible domain-wall bowing is quite negligible.

The reversible behavior of the stress-annealed Co-rich ribbon is due to the purely rotational magnetization process. The magnetizing and the magnetization-stress curves well satisfy the theoretical equations derived by Livingston for a ribbon with transverse magnetic anisotropy. The negligible magnetoelastic hysteresis makes this material particularly suitable for strain sensing applications in civil engineering.

IV. DISCUSSION

In the Jiles–Atherton phenomenological model of the magnetomechanical effect the magnetoelastic hysteresis is explained by irreversible domain-wall movements between pinning sites, which are induced by the application of stress. The domain-wall bowing and magnetization rotations, on the other hand, contribute to the reversible part of the magneto-mechanical effect. According to their empirical "law of approach to the principal anhysteretic," the application of stress induces such irreversible changes, which cause the magnetization to approach its equilibrium anhysteretic value.

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