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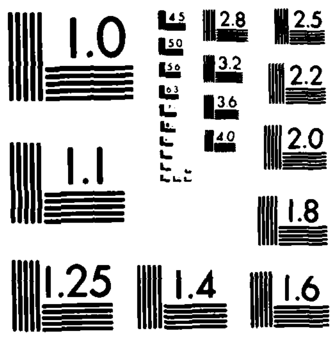

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SEM STUDIES OF MAGNETIC DOMAINS IN AMORPHOUS METALS

Final Report
Contract No. N00014-82-C-0060

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Prepared by

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Magnetic domain structures in amorphous ribbons were characterized by SEM and Bitter techniques. Studies included effects of anisotropy constant, applied currents, twisting, etc. Results were related to magnetic and magnetomechanical properties.

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Section 1

BACKGROUND

1.1 Amorphous Metals

Melt-spun ribbons of amorphous magnetic alloys, particularly alloys of transition metals such as Fe, Ni, and Co with metalloids such as B, Si, and C, have been under intensive study for several years. Their lack of grain structure and magnetocrystalline anisotropy allows the attainment of excellent soft magnetic properties. In addition, they exhibit high mechanical strength and hardness and, in some cases, high corrosion resistance. As a result, these newly available materials are being evaluated for various magnetic and magnetomechanical applications. Although their largest volume application may eventually be as core materials in distribution transformers, in the near future they appear likely to be used primarily in high-frequency and electronic applications and as transducers and sensors, e.g., sonar sensors for the Navy. For some applications, amorphous alloys may be used in the form of sputtered films rather than melt-spun ribbons.

An important feature of amorphous magnetic alloys, not yet fully exploited, is that their technical magnetic properties can be varied over a wide range by variations in annealing and processing history. These variations produce different distributions of magnetic anisotropies and magnetic domain structures, resulting in variations in ac losses, permeability, coercivity, magnetostriction, etc. Magnetic domain structures are determined largely by the specimen shape and by the orientation, symmetry, and magnitude of the magnetic anisotropies present. In amorphous metals, these anisotropies usually result from magnetic annealing and/or from internal or applied stresses interacting with magnetostriction.

1.2 Anisotropy Types

For 60 Hz transformer applications, ribbons have usually been annealed in a longitudinal field to produce *longitudinal* anisotropy, i.e., a low-energy or "easy" magnetic axis along the ribbon length. This process can produce high permeabilities, low coercivities, and square-loop magnetic behavior. Magnetization in longitudinal field occurs primarily by the motion of 180° domain walls. Eddy-current losses are proportional to the average domain width, which can be 1 mm or more, and may be nearly 100 times higher than classically calculated eddy-current losses.

Transverse anisotropy, i.e., an easy axis parallel to the ribbon width, produces maximum magnetomechanical coupling and is therefore of interest for transducer and sensor applications. Magnetization in longitudinal field occurs primarily by rotation rather than by domain-wall motion. Eddy-current losses are low, approaching the classical limit, and hence transverse anisotropy is also of interest for high-frequency applications. However, magnetostrictive length change is maximum, and the magnetic hysteresis loop is sheared, i.e., permeability is lowered.

Perpendicular anisotropy, with the easy axis normal to the ribbon plane, produces a very fine internal domain structure and a closure-domain structure at the surfaces.

Magnetization in longitudinal fields will generally involve both rotation and domain-wall motion, yielding intermediate properties.

Easy-axis orientations among these three limiting cases, or *oblique* anisotropies, can also be produced. The resulting combination of properties may be favorable for particular applications.

1.3 Pre-Contract Work

Prior to the present contract, we had studied domain structures in amorphous metals by Bitter and scanning electron microscopy (SEM) techniques,[1–6] in support of the General Electric development program for amorphous metal distribution transformers. Emphasis had been on ribbons with longitudinal anisotropy, although oblique in-plane anisotropy was also studied.[5]

We proposed in August 1981 to use our techniques to study anisotropy and domain control in amorphous metals. Special emphasis was placed on transverse and oblique anisotropies because of their importance in transducer and high-frequency applications. Domain observations were to be coupled with magnetomechanical measurements by A.E. Clark and co-workers at the Naval Surface Weapons Center (NSWC).

In preparation for the contract, a simplified model of the magnetomechanical properties of transverse-anisotropy ribbons was developed.[7] The treatment emphasizes the importance of a low and uniform anisotropy in producing high magnetomechanical coupling, and is similar to that independently developed by Spano et al.[8] Plans for specific domain experiments were developed after a visit to NSWC in November 1981.

Section 2

CONTRACT RESULTS

2.1 Publications

Work on this contract since its initiation in December 1981 has resulted in five publications in the scientific literature:

1. "Domain Studies on Amorphous Ribbons with Transverse or Oblique Magnetic Anisotropy," J.D. Livingston, W.G. Morris, and F.E. Luborsky, *J. Appl. Phys. 53*, 7837 (1982).
2. "Effects of Anisotropy on Domain Structures in Amorphous Ribbons," J.D. Livingston, W.G. Morris, and T. Jagielinski, *IEEE Trans. Magn. MAG-19*, 1916 (1983).
3. "Effects of Applied Currents on Domain Structures and Permeability in Amorphous Metal Ribbons," J.D. Livingston, W.G. Morris, and T. Jagielinski, *J. Appl. Phys. 54*, 1790 (1984).
4. "Magnetic Domains in Twisted Amorphous Ribbons," J.D. Livingston and W.G. Morris, *IEEE Trans. Magn. MAG-20*, 1379 (1984).
5. "Magnetic Domains in Amorphous Metal Ribbons," J.D. Livingston and W.G. Morris, *J. Appl. Phys. 56* (1985) (accepted for publication). This paper is largely a review paper, and is included in this Final Report as Appendix A.

The principal investigator has also been asked to participate in the May 1985 EPRI-Acta Met Workshop on Amorphous Metals and Semiconductors, which will involve the preparation of another paper reviewing the contract work and other domain studies on amorphous metals. This will appear in the workshop proceedings, to be published by Acta Metallurgica.

2.2 Oral Presentations

Since the initiation of this contract in December 1981, the principal investigator has made 10 oral presentations pertaining to the contract work:

1. July 1982 at Montreal, Canada (Joint Intermag/3M Conference) - publication 1 above.
2. January 1983 at Naval Research Laboratory, Washington, D.C. - Domains and Magnetomechanical Properties of Amorphous Metals.
3. April 1983 at Philadelphia, PA (Intermag Conference) - publication 2 above.
4. April 1983 at Toronto, Canada (ASM seminar) - Applications of Amorphous Metals.
5. November 1983 at Pittsburgh, PA (3M Conference) - publication 3 above.
6. April 1984 at Hamburg, Germany (Intermag Conference) - publication 4 above.
7. April 1984 at Ruhr University, Bochum, Germany - Magnetic Domains in Amorphous Metals.
8. April 1984 at Westphalian University, Munster, Germany - Magnetic Domains in Amorphous Metals.

9. October 1984 at Rensselaer Polytechnic Institute, Troy, NY - Magnetic Domains in Amorphous Metals.
10. November 1984 at San Diego, CA - publication 5 above.

In addition, an oral presentation will be made in May 1985 at the EPRI-Acta Met Workshop on Amorphous Metals and Semiconductors, as noted above.

2.3 Experimental Results

The highlights of our experimental results obtained during this contract are reviewed in the paper that appears as Appendix A of this report. We include here only some further experimental observations that remain preliminary in nature and will require further study before publication in the scientific literature.

We have studied numerous ribbons with transverse magnetic anisotropy induced by annealing under tensile stress. The alloys studied were Co-rich alloys with near-zero magnetostriction, and the transverse anisotropy is believed to be *creep-induced anisotropy.* The static domain structures observed (Appendix A, Figure 3) appear similar to those observed in ribbons with transverse field-induced anisotropy. However, domain-wall motion induced by applied currents was highly inhomogeneous and non-linear. Results indicated that most domain walls were severely pinned. Higher magnification studies by Bitter technique revealed that the domain walls were jagged and irregular, far less smooth than those in ribbons with field-induced anisotropy. We conclude that the creep-induced anisotropy in the ribbons studied was highly inhomogeneous, with strong local variations in the orientation and magnitude of anisotropy. This presumably results from microscopic inhomogenieties in the creep strain. More study is necessary to determine whether this is a general feature of all alloy ribbons in which anisotropy is creep induced.

Most of our domain studies have been on melt-spun amorphous ribbons, but we have also used SEM and Bitter techniques to examine magnetic domains in *sputtered amorphous films.* Samples of many alloy compositions designed to have zero magnetostriction were received from N.S. Kazama of Tohoku University, Japan. Domains observed in CoNbTi and CoNbFe films were predominantly transverse. The transverse anisotropy was believed to be induced by the 100 Oe transverse field applied during the dc sputtering. However, several CoFeSiB films sputtered under similar conditions showed partly oblique or longitudinal domains. These may have resulted from a failure to achieve zero magnetostriction, coupled with stresses induced by the substrate. However, more detailed studies are needed to fully characterize domain structures and behavior in these sputtered films.

As shown in Figure 5 of Appendix A, ribbons in which *partial crystallization* has occurred usually show fine domain structures indicative of perpendicular anisotropy. In other cases, transverse anisotropy was reported. We believe the perpendicular anisotropy is magnetoelastic anisotropy associated with biaxial compressive stresses. In some cases, we know that the crystallization occurs preferentially on the ribbon surface, and that the denser surface layers induce biaxial compressive stresses on the interior of the ribbon. In other cases, however, the crystallization is believed to be more uniform, and the origin of the biaxial compression is not clear. More work is necessary to definitively establish the effects of partial crystallization on magnetic anisotropy and domain structures in amorphous ribbons.

Section 3

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5. "Effect of Annealing Angle on the Magnetic Properties of an Amorphous Fe-B-Si-C Alloy," F.E. Luborsky and J.D. Livingston, *IEEE Trans. Magn. MAG-18*, 908 (1982).
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APPENDIX A

84CRD305

J.D. Livingston
W.G. Morris

MAGNETIC DOMAINS
IN AMORPHOUS METAL RIBBONS

Report No. 84CRD305
December 1984

MAGNETIC DOMAINS IN AMORPHOUS METAL RIBBONS

by

J.D. Livingston and W.G. Morris*
Metallurgy Laboratory

Report No. 84CRD305 December 1984

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*Materials Characterization Operation

GENERAL ELECTRIC

General Electric Company
Corporate Research and Development
Schenectady, New York 12345

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SUMMARY

The results of various static and dynamic studies of domains in amorphous metals by SEM and Bitter techniques are reviewed. Observations include domain widths and orientations, wall mobility and pinning, domain-wall energy measurements, and the effects of various distributions of residual or applied stresses on domain patterns. Domain structures resulting from longitudinal, transverse, and perpendicular anisotropies are contrasted.

*Materials Characterization Operation

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MAGNETIC DOMAINS IN AMORPHOUS METAL RIBBONS

J.D. Livingston and W.G. Morris

INTRODUCTION

For the past few years, we have employed scanning electron microscopy (SEM) and Bitter techniques to study magnetic domain structures in melt-spun amorphous metal ribbons.[1-10] Emphasis has been on Fe-rich metal-metalloid alloys such as Allied 2605S-2 ($Fe_{78}B_{13}Si_9$) because of the potential of such alloys in transformers and transducer applications. These high-magnetization alloys have a substantial positive magnetostriction, and their domain structures are very stress-sensitive. We have also studied Co-rich alloys with near-zero magnetostriction, mostly $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$. Such alloys are useful for pickup heads and other high-frequency applications.

EXPERIMENTAL

Most of our domain observations, whether with Bitter or SEM technique, were made on the shiny or air surface of the melt-spun ribbons without the need for any surface preparation. When magnetic anisotropies were sufficiently high, e.g., in Fe-rich alloys with applied or residual stresses, domain structures could usually be revealed with the simple Bitter technique, in which colloidal magnetic particles decorate the domain walls. The ferrofluids used have included kerosene-based colloids produced by A.E. Berkowitz, water-based colloids from Ferrofluidics Corp., and diluted lignosite, a water-based colloidal magnetite produced by Georgia-Pacific Corp. Usually a small drop of colloid was placed on the sample and spread into a thin layer using a cover glass. The domain structure was then viewed and photographed using dark-field microscopy on an Olympus Vanox microscope. We generally were unable to reveal domain structures in annealed, stress-free ribbons using this technique, perhaps because the low magnetic anisotropies in these materials result in wide domain walls with reduced stray fields and colloid collection.

Most of our domain observations were made using a JEOL 200 keV scanning transmission electron microscope (STEM) adapted for domain imaging by insertion of special sample stages into the large chamber between the second condenser and objective lenses.[11,12] Domain contrast in the backscattered electron signal, known as type II contrast, originates from Lorentz-force interaction of the scattered electrons with the internal magnetization of the sample. One sample stage allowed in-situ application of longitudinal magnetic fields and tensile stresses. Another allowed sample rotation and application of longitudinal fields and longitudinal currents. The stage is inserted through one port of the intermediate chamber and the detector assembly through a diametrically opposite port. Figure 1 shows the rotatable sample stage and detector assembly in proper relative position.

Because domain contrast increases with increasing beam energy, 200 keV electrons were used. A current of about 2 nA was incident on the sample, and was focused and scanned in the normal STEM operating mode. Initial domain observations were at 15X magnification, increasing up to 500X as required. Sample rotation was chosen so that the magnetization was normal to the electron beam. To optimize domain contrast and minimize topographic contrast (generally a problem with the rough surfaces of amorphous ribbons), the sample tilt and detector tilt angles were varied. Measured relative to the incident beam vector, the normal to the sample surface varied from 50 to 65° and the detector from 90 to 120° for various samples. Applying field or current to the sample helped identify domain contrast in the image.

For dynamic studies, ac magnetic fields or currents were applied to the sample during scanning, with the line scanning direction normal to the domain walls.[3] The line-scan frequency was 20 Hz, with 1000 lines and a frame period of 50 seconds. A 2 Hz applied field therefore produced 100 cycles of wall oscillation during the frame period, yielding a serrated wall image showing the amplitude of oscillation. Beating produced similar images at frequencies near a harmonic of the scan frequency. We commonly used signals near 60 Hz for dynamic studies.

LONGITUDINAL ANISOTROPY

In ribbon geometry, demagnetizing fields are minimized with longitudinal anisotropy. This is the easy axis found in as-cast zero-magnetostriction alloys and in Fe-rich alloys when given a stress-relief anneal in zero applied field. However, longitudinal anisotropy is usually induced by annealing in longitudinal field. Domain widths are typically 1 mm or greater, and decrease with increasing frequency of demagnetiza-

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Figure 1. Rotatable sample stage and detector assembly in relative position used in electron microscope for domain observation.

tion.[3] Apparently domain widths are more dependent on magnetic history than on considerations of minimum magnetostatic energy. Ribbons of higher dc coercivity (caused, for example, by rougher surfaces[13]) were generally found to have finer domains.[3] The resulting lower eddy-current losses partly compensate for the higher hysteresis losses, resulting in a relative insensitivity of *total* 60-Hz losses to coercivity.

Dynamic studies with longitudinal ac fields, e.g., Figure 2, enable study of the amplitude of wall motion as a function of field, frequency, stress, ribbon thickness, etc. Detailed analysis of the serrated images reveals any irregularities in wall motion. The pinning of some walls by specific surface defects has been directly demonstrated.[3] Measurements of pinning and nonuniformity in wall mobilities are pertinent to eddy-current calculations, which usually have assumed all walls equally mobile.

Longitudinal currents produce transverse magnetic fields that yield magnetization rotation in longitudinal-anisotropy ribbons. This rotation could be detected by contrast change in the SEM image. It also led to an increase in initial longitudinal permeability (0.2 mOe, 5 kHz), and the current to produce maximum initial permeability was found to be proportional to the longitudinal anisotropy constant K_u.[9]

TRANSVERSE ANISOTROPY

A transverse easy axis can be induced by annealing in a transverse magnetic field, but much larger fields are required than for longitudinal-field annealing.[5] Domain widths are much smaller than in longitudinal-anisotropy ribbons, decrease with decreasing ribbon width, and are relatively insensitive to demagnetizing frequency.[7] These various observations indicate that domain widths may be largely determined by demagnetizing field and considerations of minimum magnetostatic energy.

The induced anisotropy constant K_u can be varied over a wide range in a given amorphous alloy by varying annealing temperature and time. A series of transverse-anisotropy $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbons was prepared with different anisotropy constants, and average domain width was found to vary as $K_u^{-1/6}$.[8] This agreed with theoretical models allowing the local magnetization within the domains to deviate from the transverse easy axis near the sample edge.

Longitudinal magnetic fields applied to transverse-anisotropy ribbons produce magnetization rotation that is detected as decreased domain contrast.[7] A decrease in domain width with increasing field was observed for Fe-rich ribbons,[7] but not for the Co-rich alloy,[8] suggesting that the effect may be associated with magnetostriction.

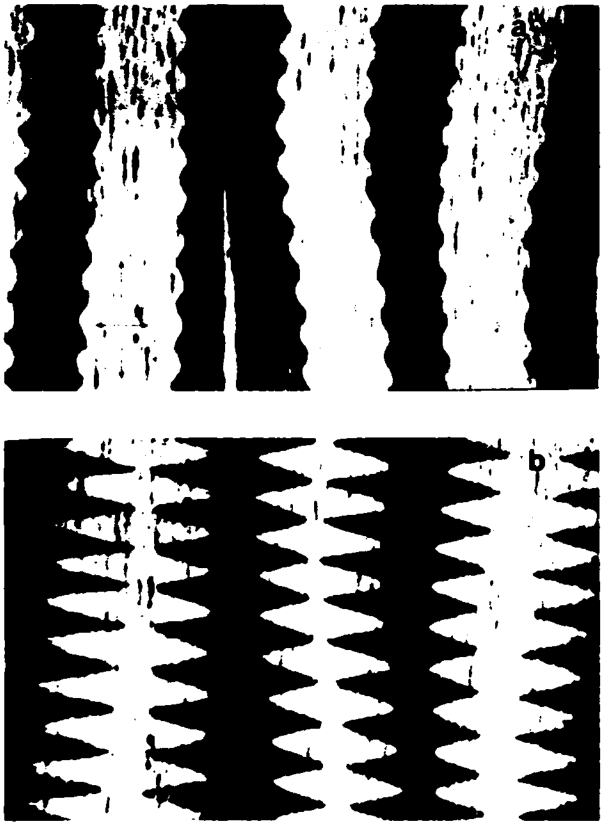

Figure 2. Serrated wall images showing amplitude of motion of longitudinal domain walls in 2605S-2 ribbon under (a) low-amplitude (b) high-amplitude ac field near 60 Hz. Arrows indicate 1 mm. (Sample received from K.S. Tan).

Longitudinal currents applied to transverse-anisotropy ribbons produce a transverse field that displaces domain walls in opposite directions on the opposite surfaces. The resulting curvature of the domain wall, measured by the displacement of the wall at the surface, can be used as a measure of domain-wall energy. Such measurements were made on the series of Co-rich ribbons mentioned above, and the variation of domain-wall energy γ with anisotropy constant K_u was determined.[9]

Transverse anisotropy can also be produced by annealing zero magnetostriction alloys under a longitudinal tensile stress.[14] A transverse domain structure produced in this way is shown in Figure 3. Current-induced wall motion in such ribbons was found to be very nonuniform and indicated strong wall pinning. These results indicate that creep-induced anisotropy is much more inhomogeneous than field-induced anisotropy. This is also clear from comparative Bitter patterns at higher magnifications, which show that

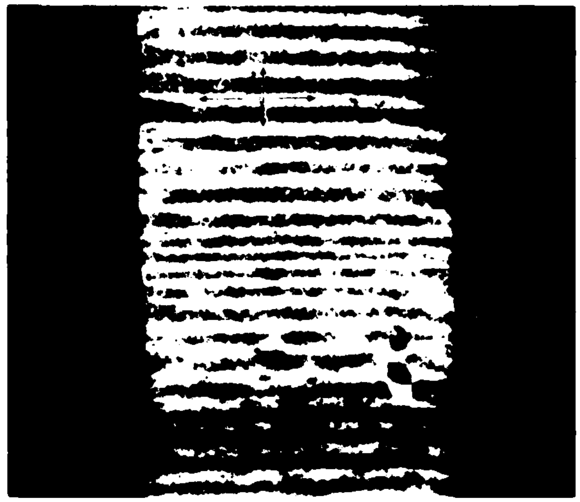

Figure 3. Creep-induced transverse domain structure in $Co_{70.3}Fe_{4.7}Si_{14.9}B_{10}Sb_{0.1}$ ribbon annealed 10 min at 410 °C under a tensile load of 722 g. Arrows indicate 1 mm. (Sample received from T. Jagielinski).

domain walls are much more irregular and ragged when anisotropy is creep-induced.

A field-induced magnetic anisotropy intermediate between longitudinal and transverse anisotropies can be produced by annealing in an obliquely oriented magnetic field.[5] Domain widths were finer than for longitudinal anisotropy, leading to a reduction in eddy-current losses.

PERPENDICULAR ANISOTROPY

When the magnetic easy axis in an amorphous metal ribbon is perpendicular to the ribbon plane, the large demagnetizing factor requires very fine domain structures to reduce magnetostatic energy. Domain widths observed are typically $10\,\mu m$ or less, and the visible domains are generally *closure domains* in these low-anisotropy, high-magnetization materials.[1] Perpendicular anisotropy can be induced by annealing in a large perpendicular magnetic field. However, in most cases the perpendicular anisotropy we have observed appears to have been due to magnetoelastic anisotropy K_σ produced by residual or applied stresses. We therefore discuss these cases in the next section.

MAGNETOELASTIC ANISOTROPY

Field-induced or creep-induced anisotropies in amorphous metal ribbons are usually much less than the magnetocrystalline anisotropies of crystalline materials. However, saturation magnetostriction λ_s in Fe-rich amorphous alloys is substantial (typically about 30×10^{-6}), and stresses as low as 1 or 2 MPa can, in some cases, be sufficient to produce a dominant magnetoelastic anisotropy.[7,15] The principal axes of the magnetoelastic anisotropy tensor are identical to those of the stress tensor.[1] In ribbon geometry, we have approximately *plane stress*, with in-plane principal stresses σ_1 and σ_2 ($< \sigma_1$). For Fe-rich, positive-magnetostriction alloys, the easy axis of magnetoelastic anisotropy will be parallel to σ_1 if σ_1 is positive (tensile). Throughout this section, we assume positive magnetostriction.

Tension

If a longitudinal tensile stress is applied to a ribbon with a field-induced oblique anisotropy K_u, the magnetization (and domain) direction rotates towards the longitudinal direction with increasing stress.[7] Measurement of local domain rotation with stress can be used as a measure of local K_u, provided λ_s is known.[16] The addition of the two anisotropies K_u and K_σ produces a net anisotropy K_{net}, given by $K_{net}^2 = K_u^2 + K_\sigma^2 + 2K_uK_\sigma \cos 2\phi$, where ϕ is the angle between K_u and the ribbon (stress) axis. Once $K_\sigma >> K_u$, of course, $K_{net} \approx K_\sigma$.

Compression

For the case of *uniaxial* compression, i.e., $\sigma_1 = 0$ and $\sigma_2 < 0$, the easy axis will be in-plane and normal to the compressive stress σ_2. The stress state on the concave side of a bent narrow ribbon approximates uniaxial compression, and, as expected, transverse domains are seen.[1] When the axes of principal stress vary with position in the ribbon, the magnetoelastic easy directions also vary. For example, a plastic point indentation leaves residual radial tensile stresses on the indented surface and radial compressive stresses on the opposite surface. This produces radial domains on the indented surface and *circular* domains on the opposite surface.[1]

For *biaxial* compression, i.e., both σ_1 and σ_2 compressive, the magnetic easy axis is no longer in-plane, and perpendicular anisotropy and associated fine domain structure results. Where $\sigma_1 = \sigma_2 < 0$, all in-plane directions are equally hard and the perpendicular anisotropy is uniaxial in symmetry. This condition was approximated by soldering a square piece of ribbon to a copper block, the contraction of the solder putting the ribbon into a nearly balanced biaxial compression. A fine network of cellular domains was produced.[1] In most cases, however, $\sigma_1 \neq \sigma_2$, i.e., anisotropy also exists in the ribbon plane and the overall symmetry is orthorhombic. A variety of fine closure-domain structures has been seen, most typically lamellar domains in a chevron or zig-zag pattern. Examples follow.

Bending

In a *narrow* bent ribbon, the stress is approximately uniaxial tension on the convex surface and uniaxial compression on the concave surface. As expected, domains are longitudinal on the former and transverse on the latter. The situation is more complex in a *wide bent ribbon*, because the ribbon shape suppresses the transverse strain component and produces a transverse stress that increases towards the ribbon center. Thus the concave surface experiences *biaxial* compressive stress, and the easy axis varies from transverse along the ribbon edge to perpendicular at the ribbon center.[1] The transition from transverse to perpendicular anisotropy results in domain structures like those in Figure 4.

Figure 4. Bitter pattern showing transition from transverse (bottom) to perpendicular (top) anisotropy in plastically bent $Fe_{81.5}B_{14.5}Si_3C_1$ ribbon. Arrow indicates 100 μm.

Twisting

As a first approximation, twisting can be represented as pure shear, with principal stresses at ±45° to the ribbon length and a helical magnetic easy axis. For a narrow ribbon subjected to small twists, domains are seen at 45°, as expected.[1] However, twisting in a ribbon geometry produces significant second-order elastic effects, in the form of longitudinal stresses that vary parabolically across the ribbon width.[10] The resulting curved domains reveal the variation of the principal stress axis with position. The complex variation of the orientation and magnitude of magnetic anisotropy across the ribbon width and through the ribbon thickness leads to other unusual domain features, including zig-zag domain walls.[10]

Residual Stresses from Processing

The rapid and nonuniform solidification produced by melt-quenching leaves a complex pattern of residual stresses. The resulting domain patterns in as-cast Fe-rich ribbons include patches of fine domains indicative of perpendicular anisotropy and biaxial compression.[1] In other areas, in-plane domains of varying orientation reflect the varying orientation of the residual in-plane tensile and compressive stresses. If field annealing is done at a temperature too low to relieve these residual stresses, remnants of the as-cast domain pattern remain.[6] If field annealing is done at too *high* a temperature, or if ribbon thickness is too great to allow adequate quenching, partial crystallization produces fine domains indicative of perpendicular anisotropy.[3,6] Alloys in which partial crystallization is intentionally induced to improve high-frequency properties[17] also show fine-domain structures (Figure 5). Alloys containing small additions of aluminum had fine domains associated with surface crystallization.[4] Cast-in boride crystals produced fine domains,[2] as did ion implantation.[1] All these cases indicate perpendicular anisotropy, probably caused by biaxial compressive stresses, although in some cases, such as in Figure 5, the origin of these stresses is not yet fully understood. We also have recently observed patches of perpendicular anisotropy in ribbons glued with cyanoacrylate to an aluminum substrate for transducer measurements.

Figure 5. Fine-domain structure indicating perpendicular anisotropy in $Fe_{75}Ni_4Mo_3B_{16}Si_2$ ribbon annealed 2.5 hr at 400 °C (in zero field) to produce partial crystallization and low loss at 50 kHz. Arrows indicate 1 mm. Longitudinal direction vertical. (Sample received from R. Hasegawa).

SUMMARY

With *longitudinal* anisotropy, domain widths are of the order of 1 mm and dependent on magnetic history. Dynamic studies of wall mobility have been useful in understanding coercivity and ac losses. With *transverse* anisotropy, domain widths are of the order of 100 μm and determined largely by demagnetizing effects and energetic considerations. Current-induced domain-wall curvature has been used to measure domain-wall energy. *Perpendicular* anisotropy yields closure domains of the order of 10 μm in width and, in Fe-rich ribbons, usually results from biaxial compressive stresses. When magnetoelastic anisotropy is dominant, domain observations can be used to analyze complex stress distributions.

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