Large Barkhausen discontinuities in Co-based amorphous wires with negative magnetostriction

J. Yamasaki
Kyushu Institute of Technology, Tobata, Kitakyushu 804, Japan

F. B. Humphrey
Electrical and Computer Engineering Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

K. Mohri, H. Kawamura, and H. Takamure
Kyushu Institute of Technology, Tobata, Kitakyushu 804, Japan

R. Mälmhäll
Royal Institute of Technology, S-100 Stockholm, Sweden

Magnetic properties, such as domain patterns and anisotropy, were measured for negative magnetostrictive Co-Si-B amorphous wires exhibiting large Barkhausen discontinuities and the results are compared to those of Fe-Si-B wires with positive magnetostriction. The Co-based wire was found to have a bamboolike domain structure at the wire surface. It was also shown that the amorphous wires prepared by the in-water quenching technique store tensile stress in the radial direction. The magnetostrictive anisotropy due to residual stress will produce an axial component of magnetization in conjunction with the two-dimensional geometry of wires making both Co- and Fe-based wires exhibit large Barkhausen discontinuities along the axis of the wire.

INTRODUCTION

Magnetostrictive amorphous wires prepared by the in-rotating water spinning method exhibit large Barkhausen discontinuities (LBD).[1] This property makes amorphous wires attractive as sensor elements in applications such as rotary encoders and high harmonics generators. We reported earlier that the LBD of Fe-based positive magnetostrictive wires is attributable to the anisotropy caused by interaction between magnetostriction and residual stresses quenched-in during solidification.[2] For a further understanding of the role of the magnetostrictive anisotropy, we measured the magnetic properties, including domain patterns, for in-water quenched Co-Si-B amorphous wires with negative magnetostriction and compared the results with those of Fe-Si-B wires with positive magnetostriction.

EXPERIMENT

The amorphous wire $Co_{72.5}Si_{12.5}B_{15}$ was produced by UNITIKA Co. (Kyoto, Japan) by the in-rotating water quenching method. The wire has a diameter of about 120 μm and a saturation magnetostriction of about -2×10^{-6}. The amorphous phase of the wire was checked by the measurement of the thermomagnetization characteristics. The Curie temperature and crystallization temperature of wire are 320 and 630 °C, respectively. Domain observation was made by the Bitter technique applying a constant 10-Oe field perpendicular to the wire axis.

RESULTS

The *B-H* loops of Co-Si-B wires are shown in Fig. 1 together with those of nonmagnetostrictive (Fe,Co)-Si-B and highly magnetostrictive Fe-Si-B wires. All loops were measured in a 60-Hz sinusoidal field in the wire axis direction. The Co-based wire [Fig. 1(a)] exhibits characteristic properties similar to the Fe-based wire [Fig. 1(c)]. When the amplitude of the drive field is below some threshold, the wire exhibits no irreversible flux change. A LBD takes place when the applied field is equal to or higher than a critical

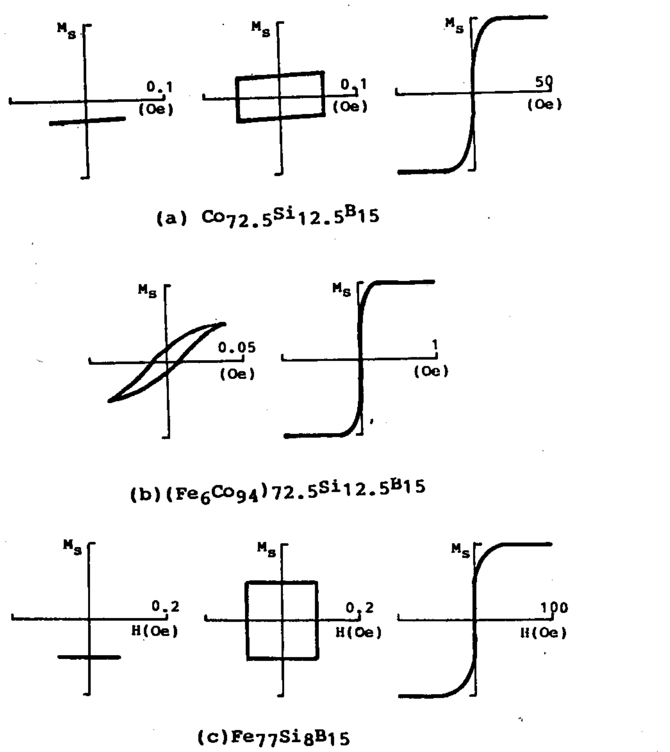

FIG. 1. *B-H* loops of as-quenched (a) Co-Si-B, (b) (Fe,Co)-Si-B, and (c) Fe-Si-B amorphous wires measured at 60 Hz.

 0021-8979/88/083949-03$02.40

reverse domain nucleation field H_n. The value of H_n and the fraction of magnetization participating in the LBD of Co-based wire are smaller than those of Fe-based wire. On the other hand, the nonmagnetostrictive Fe-Co-based wire [Fig. 1(b)] shows the very soft magnetic properties without LBD. The coercivity is less than 10 mOe and complete saturation can be achieved with an applied field of about 0.3 Oe. It is clear, by comparing the loops of the three wires, that magnetostriction is important for the occurrence of LBD. In fact, the LBD behavior of Co-based wire was found to disappear after stress relief annealing at 420 °C for 30 min, as shown in Fig. 2. The annealed wire has the soft magnetic properties similar to the nonmagnetostrictive wire.

Bitter patterns of Co- and Fe-based wire are shown in Fig. 3. The pictures show only the top surface of the circular wires, so the actual wire diameter is much larger than the visible width. These domain patterns were observed all along the surface of both wires. The Co-based wire [Fig. 3(a)] has bamboolike straight walls at the surface, while the Fe-based wire [Fig. 3(b)] exhibits the well-known maze domain pattern. The domain width is about 20 μm for Co wire and 4 μm for Fe wire. It was observed that both domain patterns do not change their configuration before and after the LBD in a low applied field. Therefore, both wires must have the component of magnetization along the wire axis in the inner core participating in the LBD.

Figure 4 shows a schematic of the domain structures expected for both wires. From the observed straight walls, the magnetization at the surface of Co-based wire is assumed to align in the circumferential direction [Fig. 4(a)]. The maze domain pattern [Fig. 4(b)] has been previouly discussed for amorphous ribbons.[3] This pattern at the surface of Fe-based wire indicates the presence of domains with magnetization perpendicular to the wire surface. The core domain size can be estimated to be about 70 and 90 μm for Co- and Fe-based wires, respectively, from the ratio of remanence to saturation. The Co-based wire has a single circular domain at the core which is covered with domains with magnetization in the circumferential direction, while Fe-based wire has a circular core covered with a closure domain structure near the surface.

The change of the core domain diameter with wire length for wires exhibiting LBD is shown in Fig. 5 as determined by the remanence-to-saturation ratio. The short-cut wires do not exhibit LBD due to the demagnetizing effect at the wire ends. The critical wire length to have LBD property is about 4 and 8 cm for Co and Fe wires, respectively. The core domain size is a very weak function of wire length,

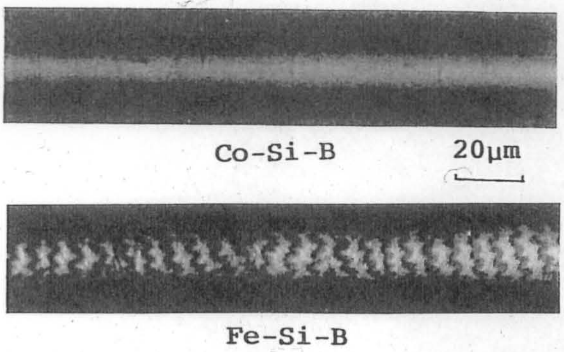

FIG. 3. Bitter patterns of Co-Si-B and Fe-Si-B amorphous wires observed with a constant applied field of 10 Oe perpendicular to the wire axis.

which suggests that the magnetostatic energy is associated for formation of inner core domain.

Figure 6 shows the distribution of the off-wire axis anisotropy in the cross section of wires evaluated from the magnetization curve measured in an applied field of 100 Oe along the wire axis for chemically etched samples. The anisotropy of Co-based wire is smaller by an order in magnitude compared to that of Fe-based wire. This difference can be attributed to the low magnetostriction of Co wire. Both wires have the higher anisotropy near the surface which decreases gradually with decreasing wire diameter.

DISCUSSION

As we have seen (Fig. 1), only the magnetostrictive, as-quenched wires exhibit LBD. This indicates that the magnetostrictive anisotropy quenched-in during solidification plays an essential role for occurrence of LBD. In general, the reverse nucleation field must be much larger than wall coercivity for materials to exhibit LBD. In the classical Sixtus and Tonks's experiment,[4] the tensile stress applied along the wire axis raised the wall energy and increased the nucleation field. The tensile stress produced a wire axis magnetization component participating in LBD, whereas it seems in amorphous wires that the tensile stress in the radial direction contributes to the increase of the nucleation field and produces wire axis magnetization in conjunction with the cylindrical geometry of wires.

The radial tensile stress in amorphous wires originates from the unique solidification process of the in-water quenching technique. When the jet of the molten alloy is ejected into the water, the outer surface first solidifies forming the solid wire diameter, and then solidification proceeds toward the inner core. During this process, the core tends to

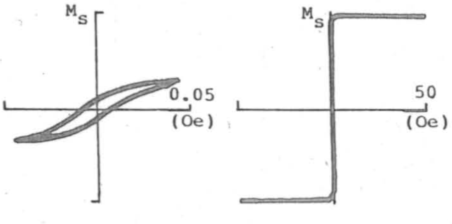

FIG. 2. B-H loops of Co-Si-B amorphous wires annealed at 420 °C for 30 min.

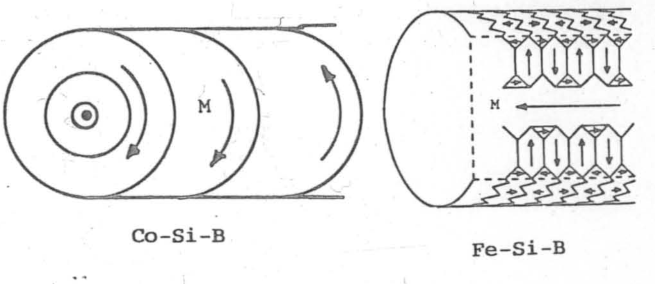

FIG. 4. Schematic domain structures assumed for (a) Co-Si-B and (b) Fe-Si-B amorphous wires.

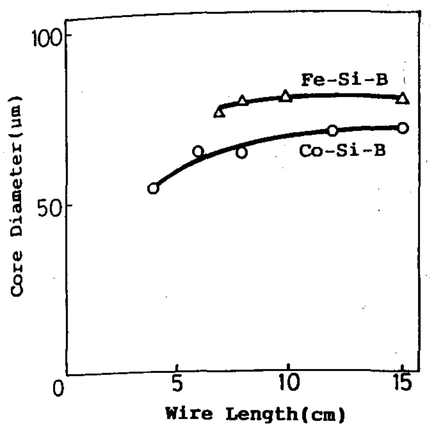

FIG. 5. Core domain size as a function of wire length for Co-Si-B and Fe-Si-B amorphous wires.

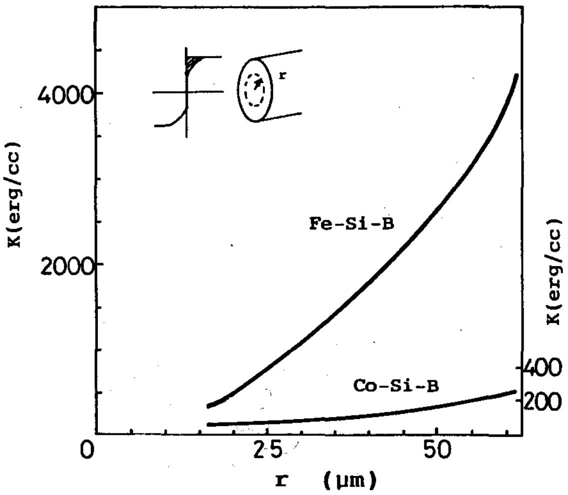

FIG. 6. Anisotropy distribution in wire cross section estimated from magnetization curve for chemically etched Co-Si-B and Fe-Si-B amorphous wires.

shrink against the surface to create tension in the radial direction. The quench rate is higher at the outer surface and decreases gradually toward the inner core. The measured off-wire axis anisotropy shown in Fig. 6 supports this model of the quenching process. Of course, the radial tension must be compensated with the compressive stress in the wire axis direction. These residual stresses would create anisotropy with the two easy axes in the circumferential and wire axis direction for Co-based wire and the anisotropy with the easy axis in the radial direction for Fe-based wire. The Bitter patterns on the wire surface in Fig. 3 are consistent with such magnetostrictive anisotropy. However, the shape effect of wire other than magnetostrictive anisotropy seems to take part for formation of the inner core single domains illustrated in Fig. 4.

In the bamboo domains of the Co-based wire, neighboring magnetic spins change their direction along the circumferential direction to store the exchange energy. The neighboring spins at the inner part make a larger angle compared to the outer spins. It is tempting to construct a model where, for lowering the exchange energy at the inner part, it is preferable for magnetization to align in the wire axis direction in the expense of magnetostatic energy near the wire ends. Thus in Co-based wire, core domain size would be determined mainly by the exchange energy. A simple calculation indicates that the core would be very much smaller than the observed size. Figure 5 shows the core diameter of the Co-based wire as a function of wire length with the Fe-based wire included for comparision. It is clear that the core is large and essentially independent of wire length. Therefore, the stress distribution must be much more complicated than our simple model assumed.

CONCLUSION

The amorphous wires prepared by the in-rotating water quenching technique store tensile stress in the radial direction. The magnetostrictive anisotropy associated with this residual stress gives rise to the wire axis component of magnetization in conjunction with the two-dimensional geometery of wires, and makes wires exhibit large Barkhausen discontinuities regardless of the sign of magnetostriction.

[1]K. Mohri, F. B. Humphrey, J. Yamasaki, and K. Okamura, IEEE Trans. Magn. MAG-20, 1409 (1984); K. Mohri, *ibid.*, 942 (1984).

[2]K. Mohri, F. B. Humphrey, J. Yamasaki, and F. Kinoshita, IEEE Trans. Magn. MAG-21, 2017 (1985).

[3]H. Kronmüller and B. Gröger, J. Phys. (Paris) 42, 1285 (1981); H. Kronmüller, R. Schäfer, and G. Schoeder, J. Magn. Magn. Mater. 6, 61 (1977).

[4]K. J. Sixtus and L. Tonks, Phys. Rev. 47, 930 (1930).