Magnetostriction measurement of amorphous wires by means of small-angle magnetization rotation

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The small-angle magnetization rotation method has been shown to be applicable for measuring the saturation magnetostriction of amorphous wires by using the circumferential field generated by an ac current through the wire. The method was used to measure compositional variation of magnetostriction of Fe-Co based amorphous wires. A saturation magnetostriction λ_s of 32.9×10^{-6} and -2.6×10^{-6} was found for Fe and Co based wires, respectively. The compositional variation of the saturation magnetostriction, λ_s, for $(Fe_{1-x}Co_x)_{75}Si_{10}B_{15}$ amorphous wires ($X = 0$–0.8) decreases with increasing cobalt content and crosses zero around $X = 0.95$ as in amorphous ribbons. The maximum experimental error of measurement was estimated to be about 5%.

INTRODUCTION

Magnetostrictive amorphous wires prepared by the in-rotating water quenching technique exhibit predominant Barkhausen discontinuities and Matteucci effect regardless of the sign of magnetostriction,[1,2] which makes amorphous wires useful as sensor elements in applications such as rotary encoders and magnetic field and electric current sensors.[3] These unique characteristics of wires were attributed to the magnetostrictive anisotropy in conjunction with the two-dimensional geometry of wires,[1] so that measurement of magnetostriction is of prime importance for investigation of amorphous wires. Because of the difficulty of using a direct measuring method, the magnetostriction of wires has been determined only by the change in magnetization curves caused by the applied stress.[4] We have developed a simple method for measuring saturation magnetostriction of amorphous wires by modifying the small-angle magnetization rotation (SAMR) technique that was developed originally for amorphous ribbons by one of the authors.[5]

PRINCIPLE

In the SAMR method that the magnetization is varied by a small angle near the easy axis of magnetization by an orthogonal ac field. The anisotropy field induced by the stress is measured as a change of dc bias field, which is necessary to cancel the effect of the induced anisotropy field. For wire, the orthogonal tickle field is generated by an ac current applied directly to the wire in the same way as in the orthogonal-type flux-gate magnetometer.[6] A schematic representation is shown in Fig. 1. If we assume the uniform ac current $I \sin \omega t$ without the skin effect, the circumferential field H_c at a point a distance r from the wire axis, the magnetization rotation angle θ, and the induced voltage V_{2f} in the sense coil can be written as

$$H_c = I\, r/2\pi a^2 \sin \omega t, \tag{1}$$

$$\sin \theta = H_c/(H_{dc} + H_k), \tag{2}$$

$$V_{2f} = -N \int d(4\pi M_s \cos \theta)/dt\, 2\pi r\, dr, \tag{3}$$

where a is the diameter of the wire, $H_k = 3\lambda_s\sigma/M_s$ the anisotropy field induced by the stress, and N the number of windings of the sense coil. We used the small-angle approximation. From these equations V_{2f} can be calculated as

$$V_{2f} = N M_s\, \omega\, I^2 \sin 2\omega t/4a(H_{dc} + H_k)^2. \tag{4}$$

Thus the second-harmonic voltage V_{2f} depends on the sum of the dc bias and anisotropy fields. When the tensile stress σ is applied with a fixed ac driving current, V_{2f} decreases due to the increase in strain-induced anisotropy field H_k. This decrease in V_{2f} can be compensated by decreasing dc bias field ΔH_{dc} to keep V_{2f} constant. Then the strain-induced anisotropy $H_k = \Delta H_{dc}$. The saturation magnetostriction can be obtained for a given σ and measured H_k as

$$\lambda_s = H_k\, M_s/3\sigma. \tag{5}$$

To determine σ (dyn/cm^2), measurement of the cross-sectional area of the wires is necessary but difficult to measure with satisfactory accuracy because of the rough surface of the wires. If we instead use tension T (dyn), which is not normalized with the cross-sectional area, Eq. (5) can be rewritten as

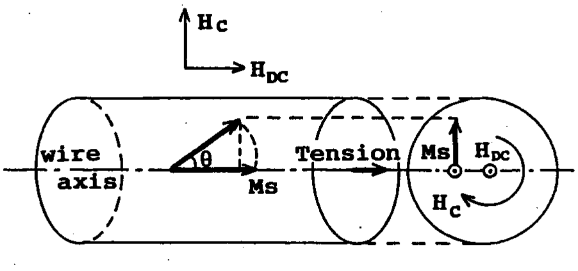

FIG. 1. Schematic presentation of SAMR. M_s is the saturation magnetization, H_{dc} a dc bias field along the wire axis to keep samples in saturation, H_c the circumferential driving field, and T the tensile stress applied along the wire axis.

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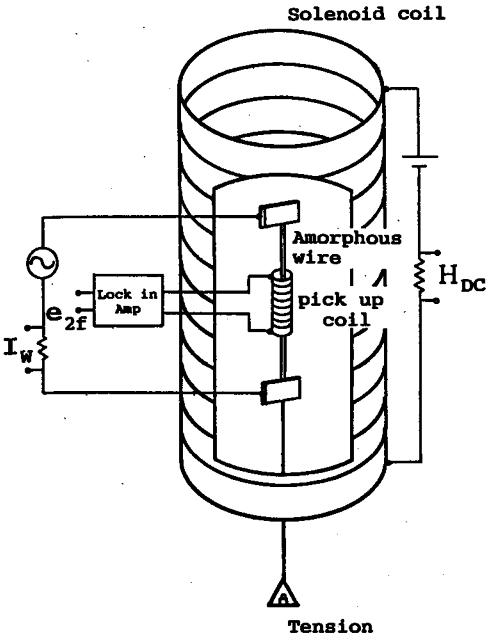

FIG. 2. Schematic presentation of apparatus.

$$\lambda_s = H_k \sigma_s W/3T, \quad (6)$$

where σ_s is the specific magnetization (emu/g) and W is the weight per unit length of the wire (g/cm).

EXPERIMENT

Figure 2 shows a schematic of the apparatus. The sense coil is 6 mm in diameter and 4 cm long with 3000 turns of 0.1-mm copper wire. Copper clamps were used at each end of the amorphous wire sample to provide electrical contact for the driving current. The 75-kHz driving current varied between 150 and 300 mA. The second harmonic was detected using a standard lock-in amplifier.

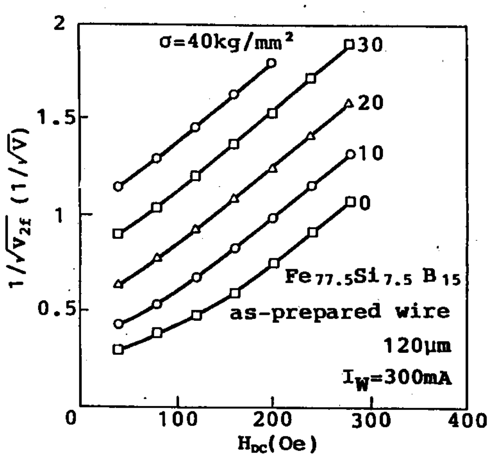

FIG. 4. $1/\sqrt{V_{2f}}$ as a function of bias field with tensile stress as parameter.

Magnetostrictive wires may have radial or circumferential anisotropy quenched-in during fabrication.[1,2] To obtain reliable magnetostriction measurements, the magnetization must be nearly parallel to the wire axis so that such off-axis anisotropy must be avoided.[7] The magnitude of this problem can be evaluated for a particular sample. As is shown in Eq. (4), $1/\sqrt{V_{2f}}$ is a linear function of the dc bias field H_{dc}. Figure 3 shows V_{2f} for Fe-Si-B amorphous wires as a function of the H_{dc} with driving current as a parameter. Linear $1/\sqrt{V_{2f}} - H_{dc}$ relations were obtained for the H_{dc} larger than 160 Oe. Extrapolation of this linear portion intersects the H_{dc} axis close to $H_{dc} = 0$, indicating the expected lack of a demagnetizing field in the circumferential direction. This is the main difference of the SAMR method between wires and ribbons.

To evaluate the minimum stress for which meaningful measurements can be made, plots of V_{2f} as a function of H_{dc} with the applied stress as a parameter can be made. As can be seen in Fig. 4, a linear relationship is found at an even lower

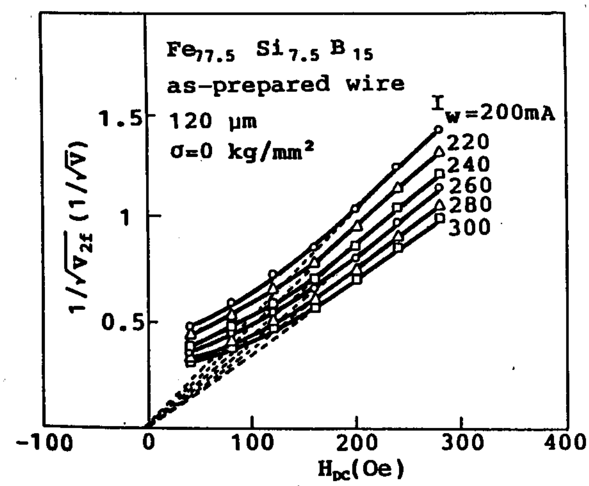

FIG. 3. $1/\sqrt{V_{2f}}$ as a function of bias field with amplitude of driving current as parameter.

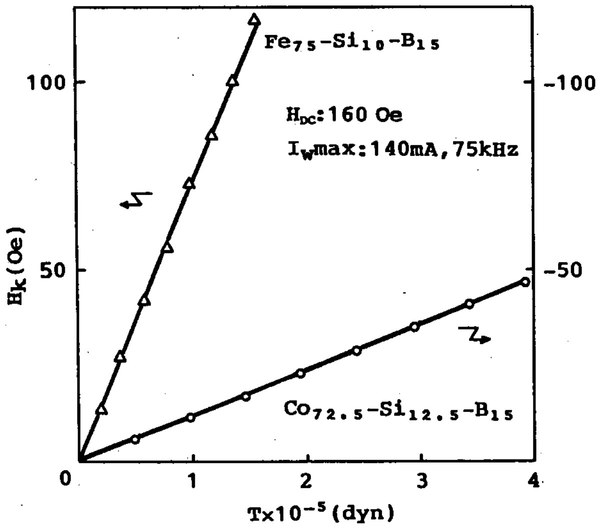

FIG. 5. Anisotropy field as a function of tensile stress T for Fe- and Co-based amorphous wires.

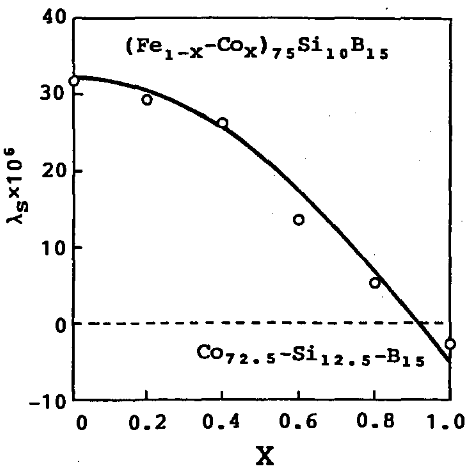

FIG. 6. Saturation magnetostriction of Fe-Co based amorphous wires as a function of Co content.

H_{dc} for reasonable values of tensile stress. For the measurements reported here, we chose an H_{dc} of 160 Oe and σ of 10 kg/mm^2 as a bias to keep wires with positive magnetostriction in saturation.

RESULTS

Figure 5 shows the anisotropy field as a function of the value of tension for Fe-Si-B and Co-Si-B amorphous wires. It can be seen that a straight line was obtained for both wires. The slope of the line gives a saturation magnetostriction λ_s of 32.9×10^{-6} and -2.6×10^{-6} for Fe and Co based wires, respectively. Figure 6 shows the saturation magnetostriction λ_s as a function of composition for $(Fe_{1-x}Co_x)_{75}Si_{10}B_{15}$ amorphous wires ($X = 0 - 0.8$) prepared by in-rotating water quenching in our laboratory and for $Co_{72.5}Si_{12.5}B_{15}$ wire made by Unitika Co. It can be seen that λ_s decreases with increasing cobalt content and crosses zero around $X = 0.95$ as in amorphous ribbons.

The error of these measurements comes from the need to measure H_k/T, σ_s and W. The total error is the root of sum of the square of these three measured values. It is estimated to be less than 5% similar to the accuracy obtained for amorphous ribbons.[5]

CONCLUSION

By applying a small circumferential field generated by an ac current through the wire, the saturation magnetostriction of thin amorphous wires can be measured easily by means of small-angle magnetization rotation. The error of measurement was estimated to be less than 5%.

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