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Magnetization Process and Domain Structure from Magnetoresistance Measurements in Thin Nickel Wires*

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From measurements of the magnetoresistance effect in thin nickel wires, conclusions are drawn about the mechanism of the magnetization process and the possible domain structure. The experimental data for the hysteresis loops of magnetoresistance are given at liquid air and room temperatures when a single magnetic field or two crossed magnetic ones are applied. The theoretical analysis using a simple model of single domain structure indicated that this is true if the magnetic anisotropy is made up of a uniaxial and a cubic magnetocrystalline component. The formation of magnetization curves composed of two or three closed loops at low temperatures is interpreted.

Rotational Model of Magnetization and Magnetoresistance

In recent years numerous investigations have been carried out on domain structure and magnetization process in specimens of small sizes. In several rotational models, the domain magnetization is assumed to rotate coherently with no domain wall motion. The magnetoresistance effect can be used as a tool in these studies because of its dependence on the orientation of domain magnetization. One expresses the relative change in resistance by:

$$\Delta R/R = a + b\cos^2\varphi + c\sin\varphi\cos\varphi + d\cos^4\varphi \quad (1)$$

since the electric current vector and the magnetization vector lie in a principal crystal plane. The constant c vanishes since the effects are truly longitudinal or transverse. φ is the angle between the magnetization I_s and the magnetic field H. The agreement between the experimental data for $\Delta R/R$ and the theoretical data corresponding to a suggested domain structure can verify the predicted magnetization process. In a single domain having mixed magnetic anisotropies with an easy direction along the [110] axis, as shown in previous works[1,2,3], one gives the relation between φ and H by:

$$h_{[110]} = (1-2j^2)j + Fi \text{ and } j = \pm 1 \quad (2)$$

$$h_{[001]} = (1.5j^2 - 0.5)j + Fj \quad (3)$$

$$h_{[100]} = (2j^2 - 1)(j + B/\sin\varphi) \quad (4)$$

where $j = \cos\varphi$, $h = HI_s/2|K|$ is the reduced magnetic field, K is the magnetocrystalline anisotropy constant, B is the reduced uniaxial anisotropy constant (in the case of shape anisotropy $F = 2B = I_s^2(N_b - N_a)/2|K|$ where N_b and N_a are demagnetization factors).

Constricted and Square Loops of Magnetization

Magnetoresistance measurements have been carried out on three different nickel wires, each 0.02 cm thick. Cathode ray oscillograph traces of $\Delta R/R$ as function of magnetic field H of the first wire are shown in Fig. 1 and Fig. 2. It can be seen that the longitudinal effect is zero. Such results may be related to magnetization square loops in domains with large uniaxial magnetic anisotropies in the direction of the wire axis. The transverse effect of the same wire shows a hysteresis phenomenon at liquid air temperatures which almost disappears at room temperature. Both magnetoresistance effects can be interpreted by means of a single domain model with an easy direction along the [110] axis. The plot of j versus h should be represented by a

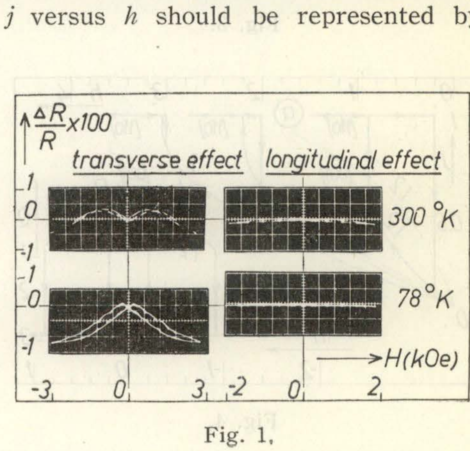

Fig. 1.

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constricted loop according to equation (2) for values of F smaller than 1. This loop becomes double since $F>1$. The formation of a typical hysteresis magnetization double-loop ($F=1.2$) is illustrated in Fig. 4-a. Equations (2) and (3) determine for still larger values of F, in a relatively large field range, non-saturated magnetization curves. The hysteresis phenomenon in $\Delta R/R$ should be associated with the second and fourth terms in the expression (1). Taking into consideration only these terms and the angles φ which satisfy eq. (2), it was possible to get a theoretical double-loop of $\Delta R/R$ as demonstrated in Fig. 4-b. The factor F decreases at low temperatures because of increasing magnetocrystalline anisotropy constant. The third term in the expression (1) may be responsible for distortion in the shape of $\Delta R/R$ traces corresponding to truly longitudinal or transverse effects. Small changes in the angle between the electric current and H produce an extreme value in $\Delta R/R$ in the case of a reversible non-saturated magnetization curve. The same term leads to less striking changes in $\Delta R/R$ at the large magnetization jumps of the magnetization double-loop. The influence of the third term can be studied experimentally, as shown in Fig. 2, if the specimen is placed in a nonuniform magnetic field or if a second field H' is applied simultaneously in the direction perpendicular to the variable field H. If the crossing field H' remains constant, the distortion in $\Delta R/R$ stemming from the third term of expression (1) will have different signs when H has values of different signs.

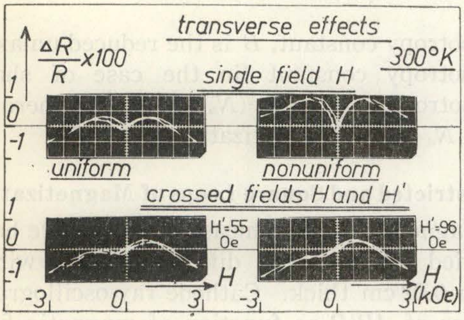

Fig. 2.

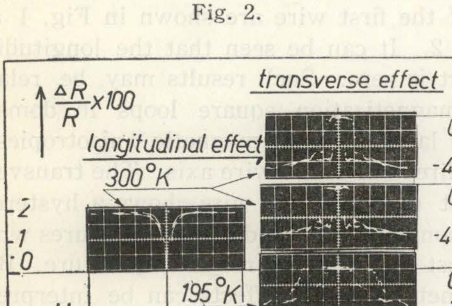

Fig. 3.

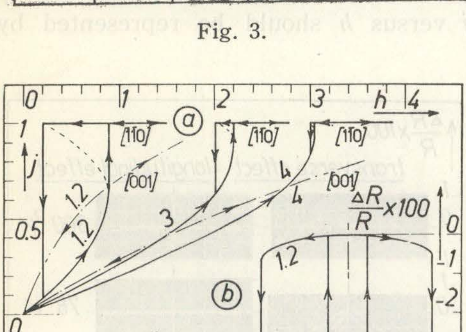

Fig. 4.

The experimental data for the second wire are shown in Fig. 3. This wire has been placed with much care, once parallel and once perpendicular, to the field H. As indicated in the figure, the double-loop of $\Delta R/R$ is more pronounced than in the case of Fig. 1. The saturation transverse effect agrees with the value 2.9% computed from equation (1) (the constants b and d have been computed according to Becker[4]). The evidence of a strong positive longitudinal effect may be associated with an arrangement of two uniaxial domains. This simple treatment is sufficient to describe closely the experimental results if the axes [110] are easy directions of the domains and if the axes [001] and [110] in the respective domains lie along the wire axis.

Triple-Loops of Magnetization

The magnetoresistance effect of the third wire is illustrated in Fig. 5. The sample has been placed in a nonuniform region of the field H. A qualitative explanation can be given by a single domain model according to eq. (4). The computed equilibrium positions of I_s are shown in Fig. 6. In an early work[3] the formation of triple-loops of magnetization at low temperatures because of these equilibrium positions has been discussed. The computed plot of $\Delta R/R$ versus h is shown in

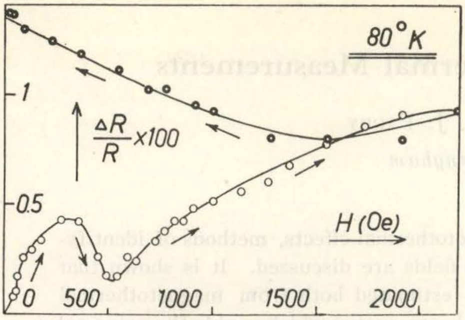

Fig. 5.

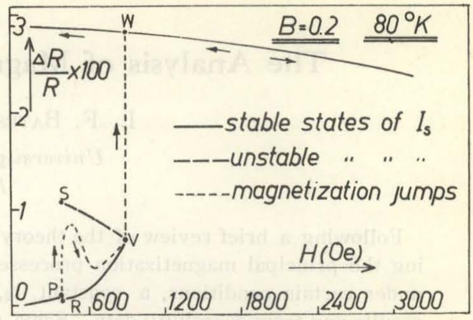

Fig. 7.

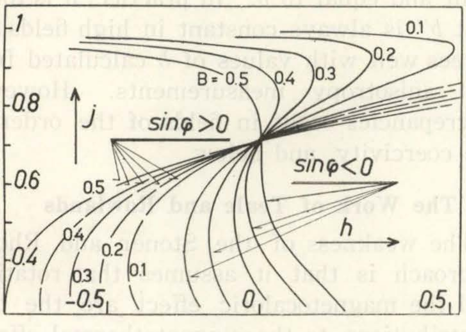

Fig. 6.

Fig. 7. The extreme value in $\Delta R/R$ observed at low magnetic field strengths can be related to a magnetization jump which occurs between different magnetization equilibrium states (branch R, V corresponding to stable states of I_s and branch S, V-to unstable states of I_s).

References

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DISCUSSION

K. Kuwahara: In Fig. 1, Prof. Hirsch compares $\Delta R/R$ versus H curve of transverse effect with the one of longitudinal effect. However, the demagnetization factor is about 2π in the transverse direction and nearly zero in the longitudinal direction, so that the longitudinal curve in the region of smaller magnetic fields (I think the field should be less than 100 oe) should be compared with the transverse curve in the region of $H=3$ koe.

A.A. Hirsch: The experimental data are plotted in $\Delta R/R$ versus H curves, where H is the measured external magnetic field. In the theoretical discussion the demagnetization factor is introduced in the magnetic uniaxial anisotropy energy.

E. Tatsumoto: We can expect that the electrical resistance could be changed by the variation of internal strain which results from the magnetostriction, especially in the discontinuous magnetization process. Did you not find such an effect?

A.A. Hirsch: Normally internal stresses do not show a preferred orientation. It is therefore impossible to explain the different longitudinal and transverse effects by internal stresses. Strains which result from the magnetostriction can change the magnetic anisotropy energy. These changes are in general small and the corresponding $\Delta R/R$ effect will be very small.