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SIMULTANEOUS MEASURING SYSTEM FOR PERMEABILITY AND RESISTIVITY OF MAGNETIC SHEET WITH DOUBLE COIL IMPEDANCE

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Abstract—**Simultaneous measuring system for permeability and resistivity of magnetic sheets is presented. In this system, the coil impedance is measured when a specimen is inserted between two coils. This system was applied to nickel sheets, iron-nickel alloys and a nickel thin film.**

I. INTRODUCTION

Planar shaped materials, such as sheets and thin films of metal, are easily available and important for applications. Therefore measurements of sample parameters without making contact to or modifying the planar shaped materials in any shape are desirable. The electrical resistivity of planar shaped materials is commonly determined by the four-point probe methods [1][2], in which electrodes must be contact to specimens. In the measurement of permeability, inductive B-H loop tracers, toroidal coils and vibrating sample magnetometers are commonly used. Since these need ring- or sphere-shaped specimens, the planar shaped materials must be modified in shape.

Eddy current methods, in which the change in the impedance of a coil close to a specimen is measured, are non-contact and non-destructive testing. By measuring the resistive and reactive components of the complex impedance, the resistivity and permeability of the specimen are simultaneously determined [3]. To correctly measure the energy loss in the specimen, it is necessary to measure the impedance in free space including the resistance of lead-lines of the coil.

We planned a simultaneous measuring system for the permeability and resistivity of magnetic sheets sandwiched between two coils [4]. By using the difference in the impedance of the two coils connected in *series-aiding* and in *series-opposing*, the resistance of the lead-lines can be nullified. In this study, this double coil method was applied to nickel sheets of a thickness ranging from 0.01 to 0.08mm, iron-nickel alloy sheets and a nickel thin film of 1μm in thickness.

II. THEORY

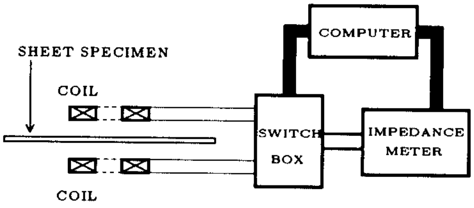

Fig. 1 Schematic of measurement equipment.

The impedance of two coils is changed with the permeability and resistivity of a magnetic sheet specimen inserted between the two coils. Both impedances of the two coils connected in series-aiding $Z_{(+)}$ and in series-opposing $Z_{(-)}$ are measured with an impedance meter by utilizing the switch box which permits the current to pass through the two coils in the same direction or in opposite directions to each other (Fig. 1). $Z_{(+)}$ and $Z_{(-)}$ are expressed as:

$$Z_{(+)} = j2\pi f(L_1 + L_2 + 2M) + R_l \quad (1)$$

$$Z_{(-)} = j2\pi f(L_1 + L_2 - 2M) + R_l \quad (2)$$

where M is a mutual inductance between the two coil containing the specimen and L_1 and L_2 are self inductances and R_l is the resistance of lead-lines and f is frequency. Then the difference between $Z_{(+)}$ and $Z_{(-)}$ is expressed as:

$$\Delta Z = Z_{(+)} - Z_{(-)} = j8\pi f M. \quad (3)$$

The theoretical formulas for ΔZ have been derived [4][5] and are expressed as:

$$\Delta Z = j2\pi f K \int_0^{\infty} \frac{D_1 D_2 e^{-\zeta d_c}}{\zeta^6}(1 - e^{-\zeta l_1})(1 - e^{-\zeta l_2}) W d\zeta \quad (4)$$

where:

$$K = 4\pi\mu_0 \left(\frac{N_1}{l_1 d_1}\right)\left(\frac{N_2}{l_2 d_2}\right) \quad (5)$$

$$D_i = \zeta^2 \int_{a_i}^{a_i+d_i} r' J_1(\zeta r') dr' \quad (i = 1, 2) \quad (6)$$

$$W = \frac{4\mu_s \frac{\eta}{\zeta} e^{\zeta t} e^{-\eta t}}{(\frac{\eta}{\zeta}+\mu_s)^2 - (\frac{\eta}{\zeta}-\mu_s)^2 e^{-2\eta t}} \qquad (7)$$

$$\eta^2 = \zeta^2 + j2\pi f \mu_s \mu_0/\rho. \qquad (8)$$

a_i, d_i, l_i and N_i are inner radius, thickness, length and number of turns of the coil. $i = 1, 2$ indicate parameters of coil1 and coil2, respectively. d_c indicates distance between the coil1 and coil2. The relative permeability, resistivity, and thickness of the sheet are denoted by μ_s, ρ and t, respectively and the size of the sheet is treated as infinite. By substituting the resistive (ΔR) and reactive (ΔX) components of the measured complex impedance to ΔZ in (4), non-linear simultaneous equations for unknown variables of μ_s and ρ. Then values of the relative permeability and resistivity can be determined by solving these equations.

III. EXPERIMENTAL

A. Measurement for nickel sheet

The permeability and resistivity of nickel sheets of a thickness raging from 0.01 to 0.08mm were simultaneously measured. All of the sheet specimens were square in shape with a side of approximately 80mm each and annealed in hydrogen at 750°C for 30 min. and slowly cooled. The coils were made by winding Polyurethane Enameled Round Copper Winding Wires (UEW) of 0.2mm in diameter on an acrylic rod of 8.0mm in diameter and the parameters of these coils are shown in Table I. The sheet specimens were large enough to treat these size of the film as infinite against the diameter of the coils since the ratio of the diameter of the coils to the side of the sheet specimens was less than 0.1. The impedance of the coils were measured in the frequency range of 1-100kHz at the coil current of 1mA.

TABLE 1

Coil parameters for measurement of nickel sheets.

Parameter	Coil1	Coil2
a (mm)	3.96	3.96
d (mm)	1.67	1.66
l (mm)	4.00	4.10
N	116	118
d_c (mm)	1.42	

In these cases, the field strength were theoretically analyzed. When the two coils are connected in series-aiding, the magnetic flux produced by the two coils is perpendicular to the surface of sheet and the field strength in the specimen is lower than 1mOe because of demagnetization. When the two coils are connected in series-opposing, the magnetic flux is parallel to the surface of sheet and the field strength is lower than 0.1Oe. Therefore the initial permeability were obtained for the coil current of 1mA.

The results of simultaneous measurements for nickel sheets are shown in Fig. 2 of relative permeability and

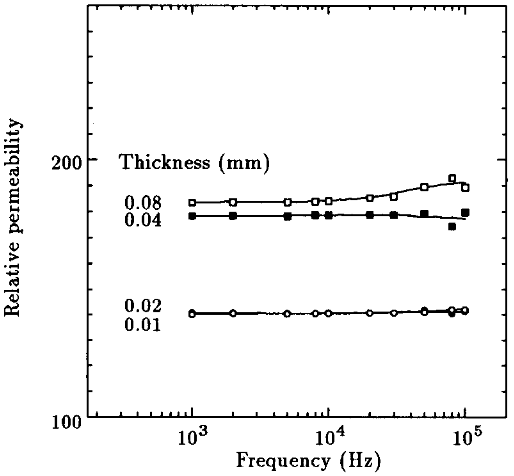

Fig. 2 Relative permeabilities of nickel sheets versus frequency for a thickness ranging from 0.01 to 0.08mm.

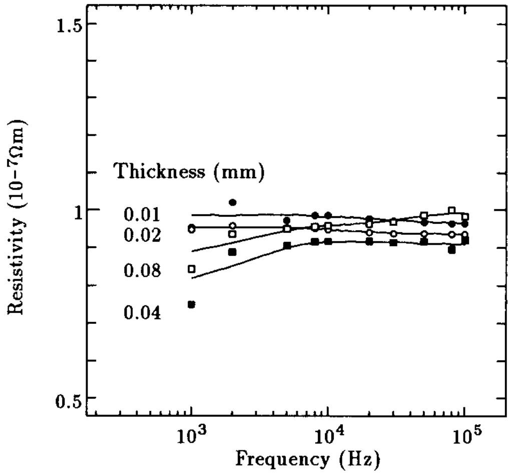

Fig. 3 Resistivities of nickel sheets versus frequency for a thickness ranging from 0.01 to 0.08mm.

Fig. 3 of resistivity. There is a large error in the resistivity measurement at frequency lower than 5kHz. This large error is caused by an inaccuracy in the impedance measurement of ΔR under 0.1Ω. At high frequency, the frequency dependance of the measured permeability is small because the effect of eddy current is added to (8). However, variations in the measured permeabilities at high frequency exist for the 0.04 and 0.08mm thick sheets. There is a similar tendency in the measured resistivities. It was discussed in [4] that these variations were caused by the frequency dependance of the method. While ΔR is depending on ρ and ΔX is depending on μ_s at low frequency, the changes in the impedance with μ_s and ρ can not be separated at high frequency then it becomes difficult to determine μ_s and ρ simultaneously with high accuracy.

B. Measurements for iron-nickel alloys

This method was applied to the permeability and resistivity measurements of iron-nickel alloys for different nickel contents of 31, 36, 42 and 45%. Specimens of 0.1mm in thickness were square in shape with a side of approximately 50mm each and annealed in hydrogen at 750°C for 30 min. and slowly cooled. Coils for iron-nickel alloy measurements were made by winding Polyester Enameled Round Copper Winding Wires (PEW) of 0.1mm in diameter on an acrylic rod of 3.0mm in diameter and the parameters of these coils are shown in Table II. The relative permeability and resistivity of the iron-nickel alloys at room temperature, which were measured with the double coil at frequency of 10kHz, are shown in Figs. 4 and 5, respectively. A peak of permeability clearly appearers at nickel content of 42%, which agrees with the behavior of permeability measured in [6]. The resistivity obtained from the double coil decreases from 8.5 to 4.6 × 10^{-7}Ωm with varying the nickel content from 31 to 45% and the relation between the resistivity and nickel content are similar to that taken from [6]. In order to show the relation between the resistivity or permeability and the nickel content varying from 30 to 100%, values for a nickel content range of 50-90% are needed and we now prepare the specimens.

C. Measurements for nickel thin film

The permeability and resistivity of 1μm thick nickel film were simultaneously measured. The specimen of nickel thin film was a disc with a diameter of 25mm and permanently supported on 3.5μm Polyester film. Spiral

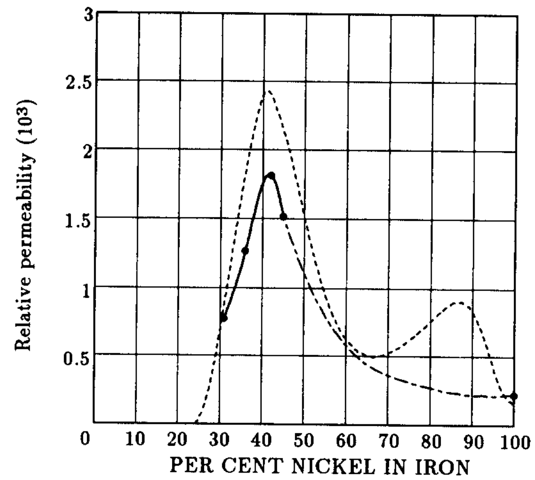

Fig. 4 Relative permeabilities of iron-nickel alloys. Closed circles indicate the permeability obtained by the double coil at room temperature. Dotted curves show the permeability taken from [6].

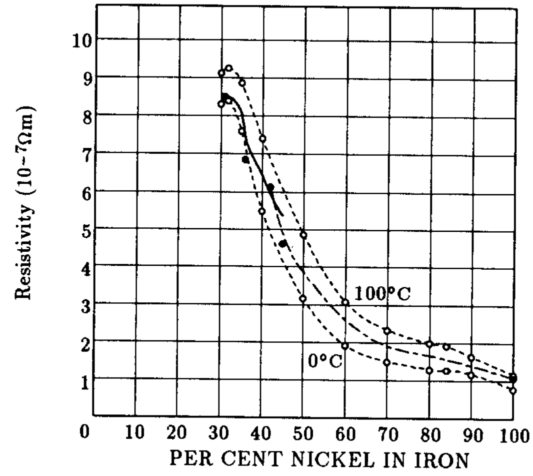

Fig. 5 Resistivities of iron-nickel alloys. Closed circles indicate the resistivity obtained by the double coil at room temperature. Dotted curves show the resistivities at 0 and 100 °C taken from [6].

TABLE 2

COIL PARAMETERS FOR MEASUREMENT OF IRON-NICKEL ALLOYS.

Parameter	Coil1	Coil2
a (mm)	1.51	1.51
d (mm)	1.02	0.86
l (mm)	5.34	4.19
N	214	203
d_c (mm)	2.33	

coils were used for the thin film measurement in order to measure the impedance at frequencies higher than few MHz. The spiral coils were made by winding PEW of 0.1mm in diameter on a acrylic rod of 3.0mm in diameter. The parameters of the spiral coils are shown in Table III. The frequency range for measurements was 1-5MHz, in which the mutual inductance between the two coils in free space was constant. As shown in Figs. 6 and 7, the relative permeability of 78 and resistivity of $8.2\times10^{-7}\Omega$m were simultaneously determined at frequencies higher than 2MHz. Both permeability and resistivity of the 1μm thick nickel film are closed to those values in bulk. Variations in the measured permeability at low frequency were caused by an inaccuracy in the measured values of ΔX increasing to 1%. A large error in the measured resistivity at frequency lower than 2MHz was caused by an inaccuracy in the impedance measurement of ΔR under 0.1Ω.

TABLE 3

SPIRAL COIL PARAMETERS FOR MEASUREMENT OF NICKEL THIN FILM.

Parameter	Coil1	Coil2
a (mm)	1.51	1.51
d (mm)	0.88	0.87
l (mm)	0.20	0.21
N	5	5
d_c (mm)	2.30	

IV. CONCLUSION

It was confirmed in this study that the relative permeability ranging from 100 to few thousands and resistivity ranging from 10^{-7} to 10^{-6} of planar shaped magnetic metals in a thickness ranging from 1μm to 0.1mm can be simultaneously measured by the measuring system with double coil impedance at a appropriate frequency. This system is easily applicable to measuring temperature dependances of permeability and resistivity, because no mechanism to move a specimen is needed in this system.

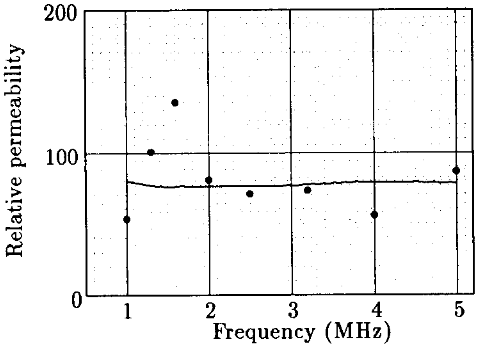

Fig. 6 Relative permeability of 1μm thick nickel film.

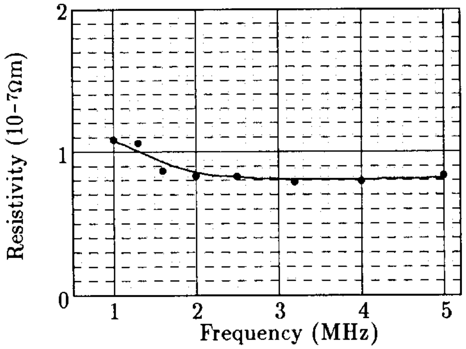

Fig. 7 Resistivity of 1μm thick nickel film.

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