Memoirs of the College of Science, University of Kyoto, Series A,
Vol. XXX, No. 1, Article 4, 1962.

FORCED MAGNETORESISTANCE IN FERROMAGNETIC ALLOYS

BY

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(Received September 26, 1961)

ABSTRACT

Forced magnetoresistance of nickel-iron, nickel-copper, iron-cobalt, and iron-platinum alloys was studied at room temperature. It was found that the forced magnetoresistance is related with the electrical resistivity by the relation $-d\rho/dH=A\rho^n$, where n and A are constants. The value of n is given as 3/4 for fcc alloy and 2 for bcc alloy. These values agree with the ones determined from the extraordinary Hall constants. It was observed that the linear relation holds between the forced magnetoresistance and the forced magnetostriction.

1. Introduction

It is generally accepted that the magnetoresistance in ferromagnetic metals and alloys is mainly due to the interaction between the *d*-electrons and *s*-electrons. This interaction has been discussed by several authors. Assuming that the main carrier in the electrical conduction is the electrons in the *s*-band, but that the electrical resistivity is determined by the scattering of the *s*-electrons to the *d*-band, Mott (**1**) calculated the electrical properties of transition metals on the basis of the collective band picture of the electronic structure. On the other hand, de Genne and Fridel (**2**), Kasuya (**3**), and Yoshida (**4**) treated theoretically the exchange interaction effect between the conduction electron and the unpaired electron localized on a particular atom in connection with the electrical resistivity. It is not clear, however, which model is more suitable to explain the magneto-resistance effect in ferromagnetics.

But, from the phenomenological point of view, the magnetoresistance in ferromagnetic metals and alloys has long been studied. The normal increase in resistivity with magnetic field observed in most metals is not absent. It appears only at low temperature, but is masked at room temperature. At higher temperatures, the magnetoresistance shows such characteristic behaviors in ferromagnetic alloys as described below. The resistivity in a transverse magnetic field is smaller than in a longitudinal one. The order of magnitude of the resistivity difference in these two directions was theoretically estimated by Smit (**5**), using the spinorbit interaction of the conduction electrons. The magnetoresistance in a single crystal depends upon the direction of electric current and of magnetic field with respect to the crystallographic orientation and also upon the symmetry of the crystal structure of the specimens. In a lower magnetic field the magnetoresistance due to the configuration of magnetic domains is observed, but in higher magnetic field the resistivity is proportional to the square of the magnetization. Above the technical saturation, there is a linear decrease of the resistivity which is called the forced magnetoresistance effect. In such a high field the magnetoresistance effects caused by the domain configuration and by the crystal anisotropy disappear and consequently the change of resistivity may be caused only by a small increase of the saturation magnetization.

The relation of resistivity *versus* magnetic field in high field was the most accurately confirmed by Smit (5) for nickel-iron alloys containing 11% iron.

Some observations have been made hitherto about the temperature dependence of the forced magnetoresistance for nickel (6), nickel-base alloys (7), and iron-aluminum alloys (8), which revealed that the forced magnetoresistance effect increases with raising temperature and falls down to small value in the temperature region near the Curie point. The relation of the forced magnetoresistance with the composition of alloy was partly observed by Smit (5) and van Elst (7), but the systematic observation over the alloy system had not been performed yet. In the present study, therefore, the concentration dependence of the forced magnetoresistance of nickel-iron, nickel-copper, iron-cobalt, and iron-platinum alloys were pursued. Nickel-base alloys were adopted because their many physical properties have already been well known; iron-cobalt alloys as the reference alloy to nickel-base alloys; and iron-platinum alloys because of the large forced effect expected by the reason to be described later.

Since the magnetoresistance effect is one of the combined effects of magnetism and electrical conduction, the results obtained will be phenomenologically discussed in connection with the electrical resistivity and the Hall effect. The discussion about the relation between the forced magnetoresistance and the forced magnetostriction will also be given in this paper, because both the effects appear at high magnetic field above the technical saturation and are caused by a small increase in the magnetization.

2. Experimental

Electrolytic nickel of 99.96% purity, electrolytic iron of 99.96%, electrolytic copper of 99.95%, platinum of 99.95%, and cobalt of 99.5% were used as raw materials. Properly mixed raw materials were melted in a high frequency vacuum furnace. The composition of the alloy was covered over the whole range of composition for nickel-iron (crystal structure fcc and bcc) and iron-cobalt alloys (bcc and hcp); up to 41% copper for nickel-copper alloys (fcc); and from 26.5 to 35% platinum for iron-platinum alloys (fcc). Concentration has been expressed in atomic per cent in the present paper. After cold-working the alloys were annealed at 1000°C for 1 hour in vacuum, then cooled slowly in the furnace down to room temperature. To obtain the disordered state of specimens, the nickel-iron alloys containing 70–80% nickel were cooled slowly from 1000°C to 600°C and then quenched down to room temperature. Alloys of iron-platinum were quenched from 1000°C to room temperature to prepare the disordered specimen. The specimens were 15 mm in length, their cross-sections were squares whose sides were 0.7~0.9 mm. The contents of the alloying elements were analysed by the spectroscopic photometry. By electric welding platinum lead wires of 0.2 mm in diameter were attached to the specimens. The electrical resistance was measured from a potential drop in the specimen by a K2-type potentiometer against a galvanometer (sensitivity 1×10^{-7} volt). The specimen holder was inserted into the Dewar vessel placed between the pole pieces of an electromagnet. The distance between the pole pieces was 30 mm, the diameter of pole pieces 43 mm, the maximum applied field in this condition 22700 Oersted. Although the transverse magnetoresistance and the longitudinal one were measured for several specimens at room temperature, no difference in the forced magnetoresistance was observed within the accuracy of the measurement. The magnetoresistance, therefore, was measured only in the transverse magnetic field, because in such orientation the higher magnetic field could be applied than the case of longitudinal magnetic field.

The temperature dependence of the forced magnetoresistance was measured for the nickel-iron alloy containing 40% nickel and the iron-platinum alloy containing 26.5% platinum from liquid nitrogen temperature up to the temperature above the Curie point, because their forced effects were large enough to be measured. For the low temperature measurements the boiling point of liquid nitrogen and the sublimation point of solid carbon dioxide were used. For room temperature and higher temperature region, a Dewar vessel, an oil bath, and an electric furnace were used for each temperature range. The stability of temperature was within 0.05° during the measurement. The accuracy of the forced magnetoresistance was estimated to be within ±2 per cent.

3. Results and discussions

An example of the behavior of the electrical resistivity in the magnetic field is shown in Fig. 1 for nickel-iron alloys. The forced magnetoresistance effect is expressed by the gradient of the linear part of the resistance-magnetic field curve. For each alloy system, the dependence of $\rho^{-1}(d\rho/dH)$ on the composition of alloys is shown Figs. 2a and 2b. The results obtained for nickel-iron alloys show a fairly good agreement with the results obtained by Smit (5), Belov and Ped'ko (9).

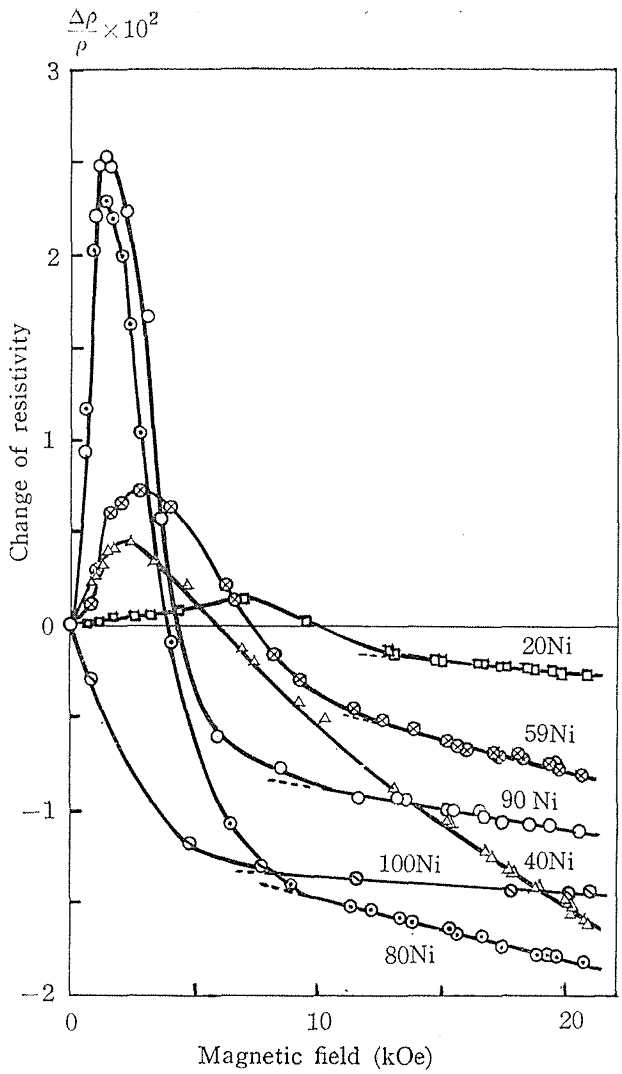

Fig. 1. Transverse magnetoresistance of Ni–Fe alloys at room temperature. The compositions are shown in atomic per cent of nickel.

In ferromagnetic metals the electrical resistivity may have been caused by the scattering of electrons with the impurity atoms, thermal vibration of the

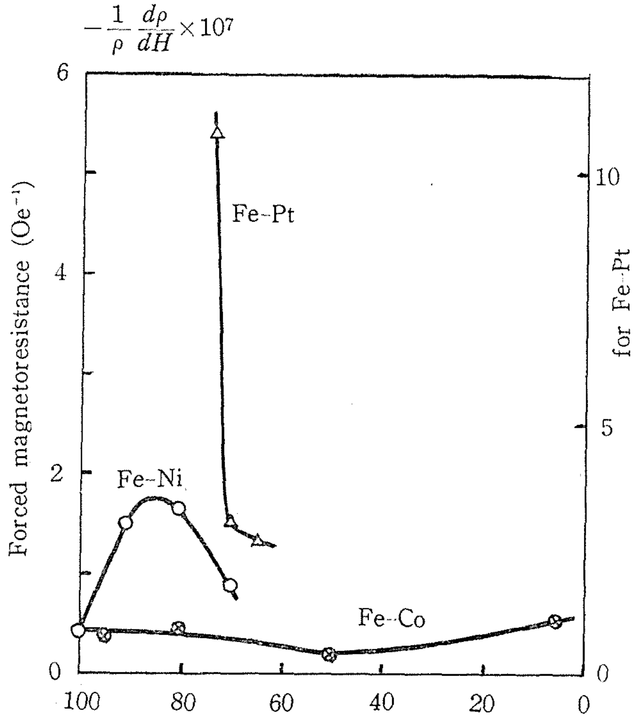

Fig. 2a. Forced magnetoresistance of Ni-Fe and Ni-Cu alloys at room temperature.

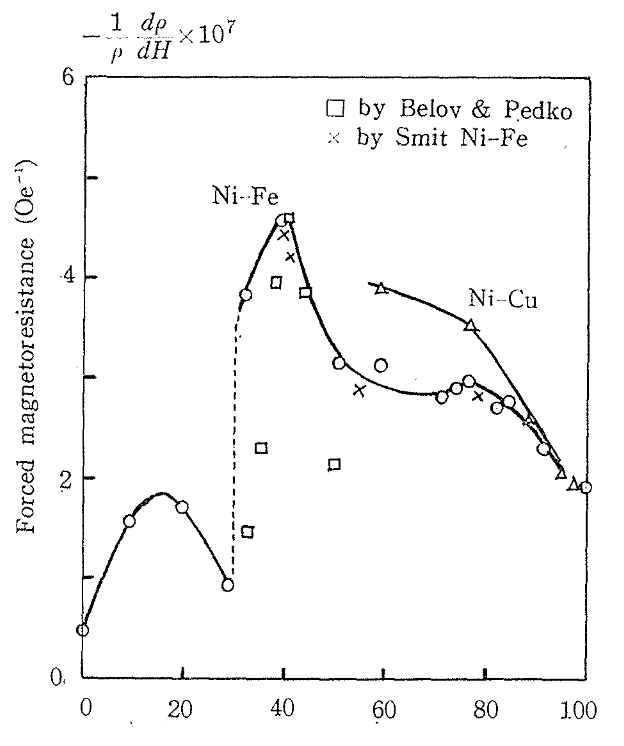

Fig. 2b. Forced magnetoresistance of Fe-Ni, Fe-Co, and Fe-Pt alloys at room temperature.

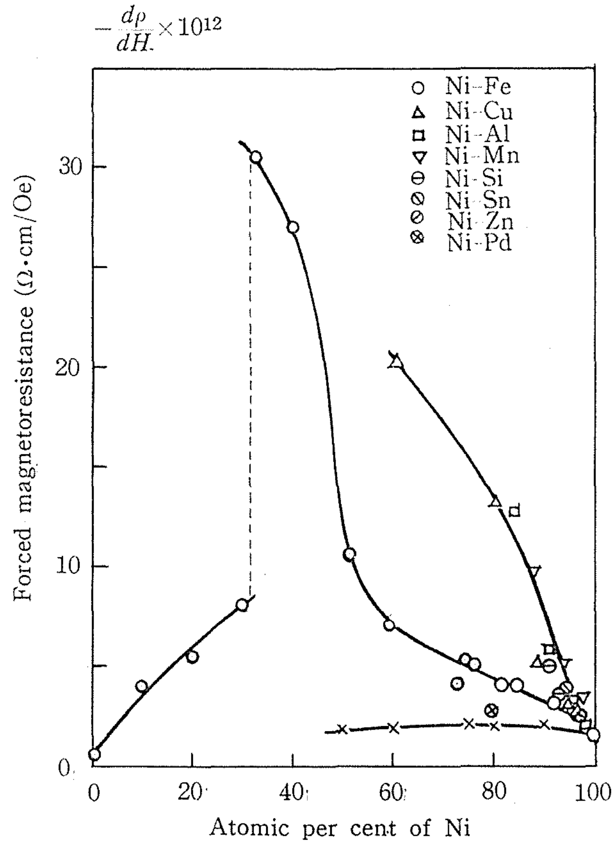

Fig. 3a. Forced magnetoresistance of iron-base alloys at room temperature.

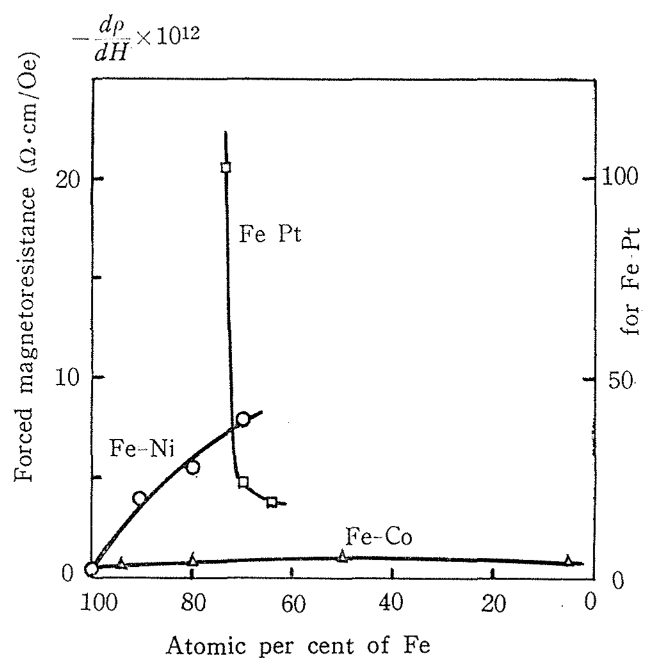

Fig. 3b. Forced magnetoresistance of Fe-base alloys at room temperature.

lattice atoms, and disordered arrangement of spin of magnetic electrons. It seems to be more proper, therefore, to think that the magnetoresistance effect is expressed as $d\rho/dH$ instead of $\rho^{-1}(d\rho/dH)$. Dependence of $d\rho/dH$ on the composition of alloys is shown in Figs. 3a and 3b. The values of $d\rho/dH$ for the other nickel-base alloys calculated from the results of Smit (5) and van Elst (7) were also plotted in Fig. 3a, and those for nickel-base alloy containing aluminum, silicon, tin, manganese, and vanadium lie nearly on the same curve of nickel-copper alloy.

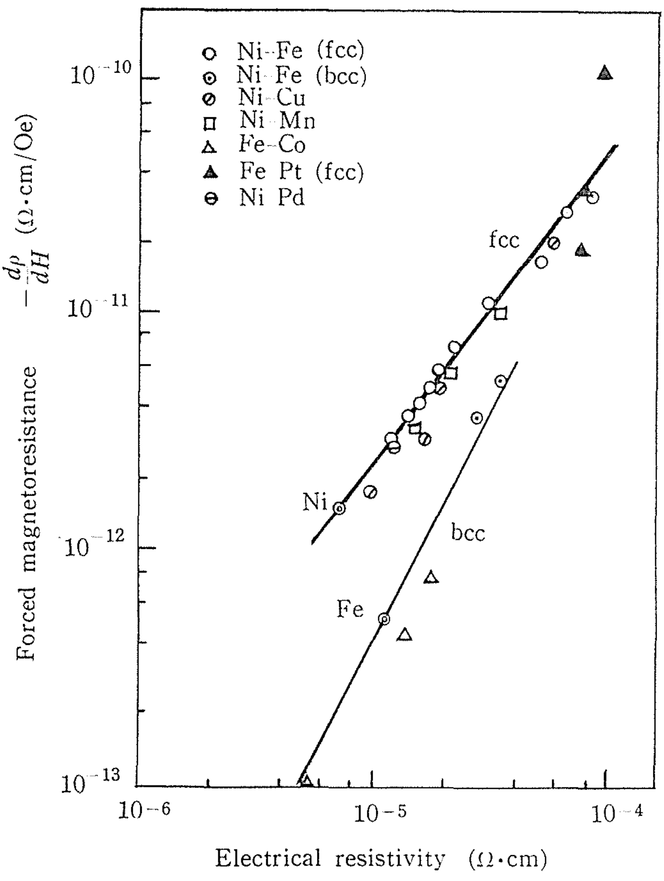

Fig. 4. The relation between the electrical resistivity and the forced magnetoresistance for ferromagnetic alloys.

The relation between the forced magnetoresistance and the electrical resistivity is shown in Fig. 4. As it is easily seen from this figure, the observed values lie on the two straight lines which correspond to the fcc crystal structure and the bcc one, respectively. Accordingly, it turns out that the forced magnetoresistance and the electrical resistivity are connected by the following relation as:

$$-d\rho/dH = A\rho^n, \tag{1}$$

where n and A are both constants. The values of the constant n is 1.33 for fcc alloys and 2.0 for bcc alloys, respectively. Now, by alloying of one atomic per cent of solute, both the magnetoresistance and the electrical resistivity of pure nickel change as shown in Fig. 5. It is seen that for the alloying elements with

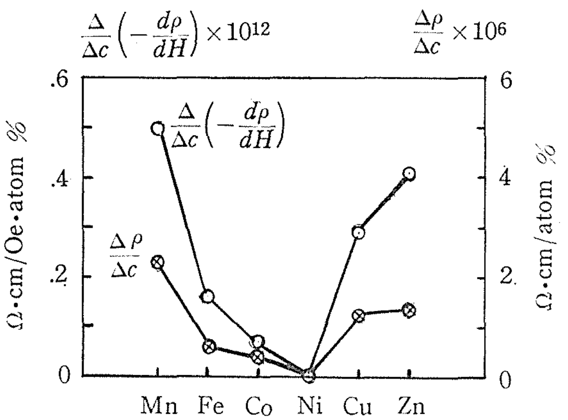

Fig. 5. Influence of alloying elements on the electrical resistivity and on the forced magnetoresistance of nickel.

d-shell filled more than half the changes of the two properties are closely connected with each other. By the addition of one atomic per cent of the other elements to pure nickel, the quantity $(\Delta/\Delta c)(-d\rho/dH)$ is linearly related with those $\Delta\rho/\Delta c$ in Fig. 6. These facts can be understood from the following form derived by differentiation of Eq. (1) with respect to the concentration c,

$$-(d/dc)(d\rho/dH) = nA\rho^{n-1}d\rho/dc, \tag{2}$$

where ρ^{n-1} will be the resistivity of pure nickel, and so becomes constant. Consequently the relation given by Eq. (1) is expected to be valid for several other alloy systems.

The influence due to the addition of copper and iron to pure nickel as shown in Fig. 3a may be understood by Eq. (1). From Fig. 5, the alloying of one per cent of copper affects the electrical resistivity of pure nickel more strongly than in the case of alloying of iron. This fact agrees with the results by Fridel (**10**) that the screening radius of copper atom in nickel lattice is larger than that of iron atom. The result of the magnetoresistance may be explained similarly by the consideration of Eq. (1).

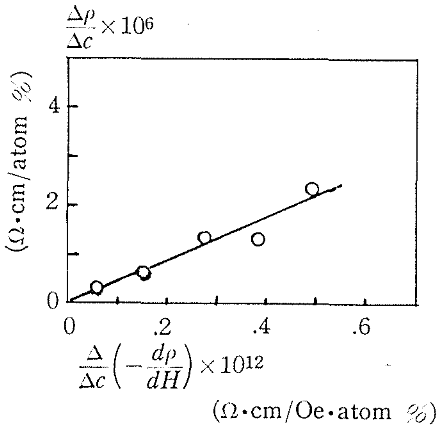

Fig. 6. Relation between the influences of alloying elements on the electrical resistivity and on the forced magnetoresistance of nickel.

On the other hand, Kooi (**11**), Schindler and Salkovitz (**12**) pointed out that the extraordinary Hall constant R_1 is related to the electrical resistivity in the following relation $R_1 = B\rho^n$, where n and B are both constants. The values of n determined from the Hall constants nearly agree with the ones from magnetoresistance for fcc and bcc alloys, respectively. Calculating the extraordinary Hall constant of the transition metals, Karplus and Luttinger (**13**) obtained 2 as the value of n. Assuming the suitable perturbation potentials in the metal, Smit (**5**) obtained 1, 1.5 or 2 as the same value of n. It is interesting that the value of n as determined from the experiments is 2 in bcc alloys and 4/3 in fcc alloys for both forced magnetoresistance and Hall constant. The difference of the values of n in the two crystal lattices has not been explained yet. From the above-mentioned consideration, it might be expected that $d\rho/dH$ is related to R_1 as $d\rho/dH = KR_1$, where K is constant. For nickel-copper and bcc nickel-iron alloys this relation seems to be valid (Fig. 7).

Next, the relation between the forced magnetoresistance and the forced magnetostriction will be discussed, because the both phenomena are considered to be due to the small increase in the magnetization at high magnetic field. Fig. 8 shows that the relation between the two forced effects is expressed by a straight line for each alloy system, but for nickel-iron alloy by two straight lines because of their different structures. Below the technical saturation the linear relation between the magnetoresistance and the magnetostriction was reported for nickel and iron by Kornetzky (**14**). But, in the present experiment, the linear relation

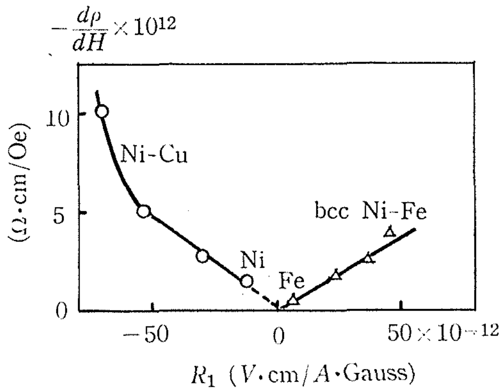

Fig. 7. Relation between the forced magneto-resistance and the extraordinary Hall constants.

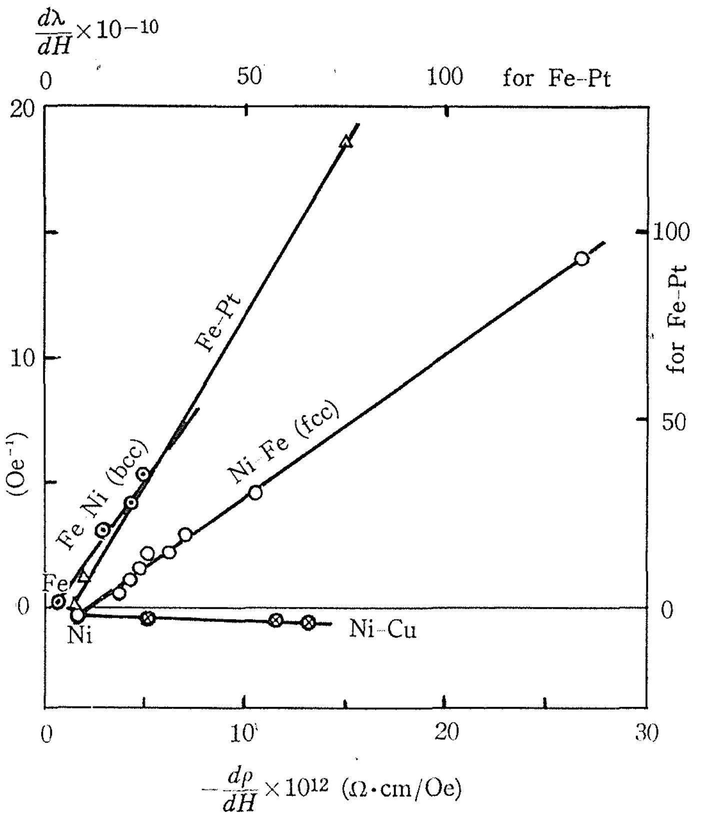

Fig. 8. Forced magnetoresistance *versus* forced magnetostriction of Ni-Fe, Ni-Cu, and Fe-Pt alloys at room temperature.

does hold in the region of magnetic field above saturation, whatever the composition of alloy may be. Assuming that the electrical resistivity is a function of magnetization, the relation $d\rho/dH=(d\rho/dI)(dI/dH)$ is obtained by differentiation. The similar one $d\lambda/dH=(d\lambda/dI)(dI/dH)$ also holds for magnetostriction. Accordingly, the linear relation in Fig. 8 means the linear relation between $d\rho/dI$ and $d\lambda/dI$. It is well known that below the technical saturation the following relations hold, namely $\rho-\rho_0=a(I^2-I_0^2)$ and $\lambda-\lambda_0=b(I^2-I_0^2)$. In higher magnetic field above technical saturation, another simple relation between the magnetization and the magnetoresistance or the magnetostriction is expected.

The temperature dependence of forced magnetoresistance was observed for nickel-iron alloy containing 40% nickel and iron-platinum alloy containing 26.5% platinum, as shown in Fig. 9a. In Fig. 9b, a similar relation between the two forced effects is shown. The relation seems to be applicable to temperature change and composition change in most cases, especially inspite of their complex nature such as nickel-iron alloy.

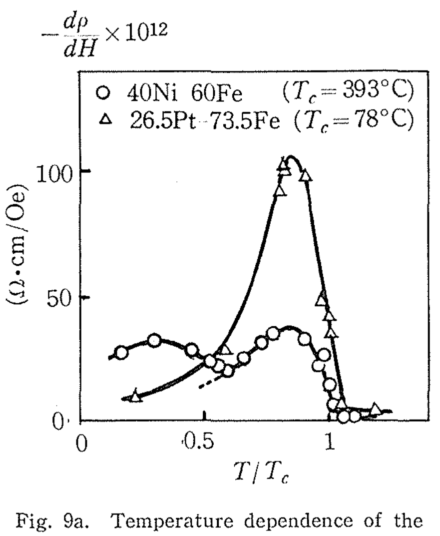

Fig. 9a. Temperature dependence of the forced magnetoresistance of Ni–Fe and Fe–Pt alloys.

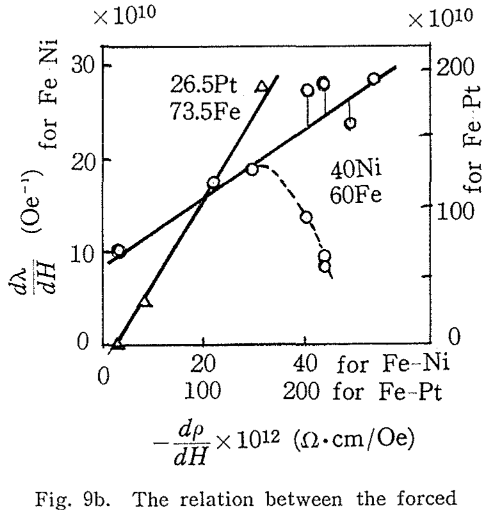

Fig. 9b. The relation between the forced magnetoresistance and the forced magnetostriction with temperature variation.

The results of nickel-iron alloy containing 40 and 36% nickel show considerably higher values than the ones for the more nickel-rich alloys. For nickel-iron alloy, the sign of ordinary Hall constant changes from negative to positive at 50% composition. Moreover, the phase transformation from fcc to bcc crystal structure must be considered, and the existence of antiferromagnetism has been discussed by several authors. This problem remains unsolved yet. The properties of iron-platinum alloy are not known so well, but from its phase diagram a similar behavior will be expected for 26.5% platinum alloy.

4. Conclusion

Forced magnetoresistance and the electrical resistivity for nickel-iron, nickel-copper, iron-cobalt, and iron-platinum alloys are connected by the relation $-d\rho/dH = A\rho^n$, where constant n is given as 4/3 for fcc alloy and 2 for bcc alloy. This relation is expected to be valid for nickel-base alloys with transition metals having the d-shell filled more than half. The linear relation between the forced magnetoresistance and the forced magnetostriction was observed over the alloy system.

Acknowledgement

The author wishes to express his hearty thanks to Prof. H. Takaki for his constant encouragement throughout this work, and to Mr. T. Nakajima for his offering the data of the forced magnetostriction before publication, and to Mr. K. Doi and Mr. K. Iwauchi for their helpful assistance in the measurement. He is also much obliged to Prof. T. Takiyama, former President of Doshisha Womens' College, for his offering him the chance of study. He is also indebted to Dr. Y. Nakamura for his valuable discussion.

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