Sci. Annals, Fac. Phys. & Mathem., Univ. Thessaloniki, **13**, 241 (1973)

TEMPERATURE DEPENDENCE OF THE HALL EFFECT IN AN ORDERED NI_3Mn ALLOY

by

I. A. TSOUKALAS and H. PAPADIMITRAKI-CHLICHLIA

Department of Physics, University of Thessaloniki

(Received 28.8.1973)

Abstract: *The Hall effect in an ordered sample of 77 Ni- 23 Mn % at. is studied as a function of temperature and the magnetic saturation and the number of effective electrons per atom are computed.*

INTRODUCTION

It is widely accepted (1,2,3,4) that the Hall effect in ferromagnetics, is given by the empirical relation :

$$e_H = R_0H + 4\pi J R_1 \tag{1}$$

where e_H is the Hall electric field per unit current density, H the magnetizing field, J the magnetization, R_0 and R_1 the ordinary and extraordinary Hall constants respectively.

R_0 is indentified as the Hall coefficient in non ferromagnetic metals.

Since the magnetic induction is known to be :

$$B = H + 4\pi J \tag{2}$$

where $J=J_s$, i.e. the saturation magnetization, for the regions above technical saturation, relation (1) becomes :

$$e_H = R_0B + (R_1 - R_0)4\pi J_s \tag{3}$$

According to the theory of a single conduction band in metals, the ordinary Hall coefficient is given by the formula :

$$R_0 = -\frac{1}{Nn^*e} \tag{4}$$

where N is the number of atoms per unit volume, n^* the number of

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

conduction electrons per atom and e the magnitude of the electronic charge in coulombs.

The value of n_s i.e. the number of 4s electrons per atom, thus resulting aggree (5) only within a factor of two with the one deduced from magnetic data.

In 1948, Sondheimer (6) proposed a relation giving R_0 as :

$$R_0 = -\frac{1}{Ne}\left[\frac{1}{n_s}\left(\frac{\sigma_s}{\sigma}\right)^2 - \frac{1}{n_d}\left(\frac{\sigma_d}{\sigma}\right)^2\right] \qquad (5)$$

where n_s and n_d are the number of 4s electrons and 3d holes respectively. σ_s and σ_d designating the electrical conductivities associated with the two bands.

In 1955, Emerson Pugh (7) proposed a more generalised four band model in which the 3d and 4s bands are divided into sub-bands, where the spins of the electrons are aligned either parallel or antiparallel to the magnetic field.

The Pugh model is thus taking into consideration the effects arising from the ferromagnetic properties of the Fe,Co,Ni transition elements. The formula proposed by Pugh is :

$$R_0 = -\frac{1}{Ne}\left|\frac{1}{n_{sp}}\cdot\left(\frac{\sigma_{sp}}{\sigma}\right)^2 + \frac{1}{n_{sa}}\left(\frac{\sigma_{sa}}{\sigma}\right)^2 - \frac{1}{n_{dp}}\left(\frac{\sigma_{dp}}{\sigma}\right)^2 - \frac{1}{n_{da}}\left(\frac{\sigma_{da}}{\sigma}\right)^2\right| \qquad (6)$$

The indices a and p designate here the division of the two bands into four sub-bands indicating parallel or antiparallel aligment of the magnetic moments of the electrons to the applied magnetic field.

Foner - Allison - Pugh (8) investigated the Hall effect in nickel manganese alloys as a function of order.

Since then no paper has been issued-to the best of our knowledge-concerning the temperature dependence of the effect in these alloys, the aim of this paper beeing to investigate such a dependence as wel] as the dependence of the saturatuon magnetization versus temperature.

EXPERIMENTAL PROCEDURE

The samples were furnished by Goodfellow Metals LTD, England and were 77 Ni - 23Mn at % of composition.

The samples were cut to rectangular form and were $2 \times 4 \times 0{,}02$ cm^3 in dimensions.

They had the same heat treatment as described in (8) in order to obtain the same sample ordering.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

The samples were heated to 470° C for seven days then cooled slowly in five days to 350° C and then cooled in one day to room temperature.

The Hall probes were spot welded to samples, the wires used as potential leads were of the same material in order to avoid any voltages arising from a bimetallic contact.

According to relation (1) the Hall emf is inversely proportional to the sample thickness and it was therefore desirable to obtain the finest thickness possible, which would permit easy detection of the phenomenon without introducing uncertainties in thickness estimation and large thermal drifts. A current density of 20 A. cm^{-2} was used.

The measurements were made by a d.c. method. The reason is that a.c. methods which are mostly used in investigating Hall effect in semiconductors introduce in the investigation of ferromagnetic material large spurious voltages, which minimize the Hall emf.

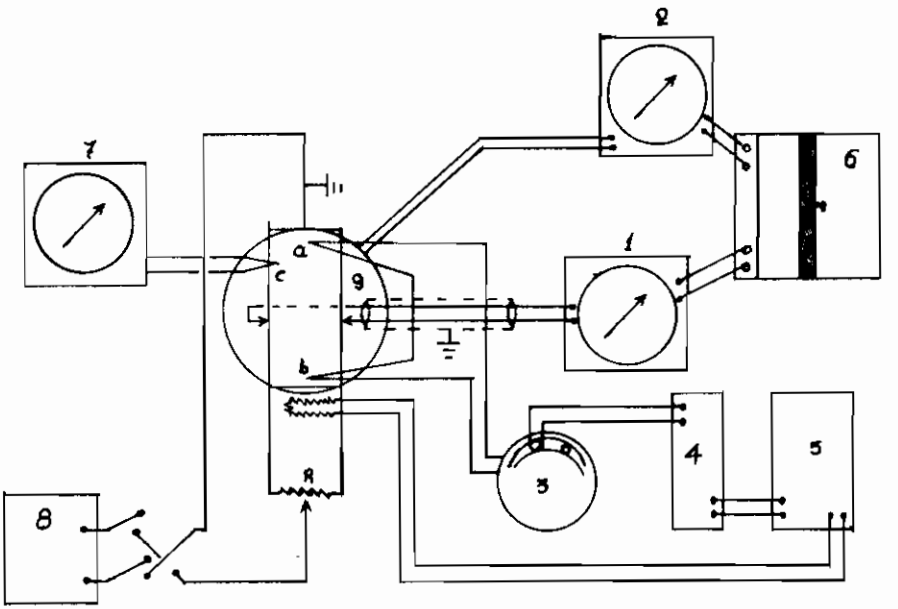

Fig 1. *Schematic diagram of the set up used.*
1 *Mieravoltmeter*, 2 *Integrating Gaussmeter*, 3 *Galvanometer* 4 *High gain amplifier*, 5 *Power amplifier*, 6 *XY Plotter*, 7 *Galvanometer*, 8 *DC Power Supply*, *R high quality variable resistor*.

The main problem of a Hall emf measurement consists in obtaining great sensibility of the setup and stable conditions during the mea-

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

surement. The measurements were made with a setup schematic diagram of which is represented in Fig. 1.

The samples after annealing were thoroughly cleaned with aqua regia and were engraved in the sample holder consisting of a thick mica foil. The lead wires were carefully mounted in order to avoid any leakages and to minimize the unavoidable loops, voltage introducing during magnetic field changes.

A high quality 1 Ohm resistor connected at contacts b as in Fig. 1 served to adjust the equipotential surface at the Hall contacts.

The contacts made on the Hall leads were inserted to a heavy brass tube with large heat sinks, in order to ensure thermal stability.

Two iron-constantan thermocouples were mounted on the sample.

The first of them served to detect any longitudinal thermal drifts in the sample and the second differential thermocouple mounted in the vicinity of the Hall probes to detect temperature differences between them. The thermocouples were spot welded under inert gas atmosphere and were calibrated with the zero point method. Their curves thus obtained checked against the International Critical Tables. They were found to be moderately accurate within a ± 1 % margin of error.

The Hall emf was measured at each field value with the magnetic field reversed and the two readings were then substracted and halfed. The main source of thermal drifts is the drift of the sample current power supply, the losses in the sample due to the changing of the magnetic field and the Ettinghausen effect.

A small thermal drift is also imposed by the primary current which at room temperature was never found to exceed 0,4° C and therefore its potential contribution was negligible.

At higher temperatures any temperature difference detected by the differential thermocouple was sensed by a photo resistance mounted on the front panel of the galvanometer and the signal was then amplified through a gower amplifier of high gain whose current served to heat a small heating element mounted on the sample in a way counterbalancing the temperature difference.

The assebly, consisting of the sample holder, sample and thermocouples was covered both sides by successive layers of mica, asbestos foils and thermal reflectors was inserted between two heating elements made on mica by bifilar winding of Kanthal Al flat strips.

The assembly was put in a small rectangular box, $12 \times 14 \times$ $\times$ 2,3 cm³ in dimensions, made from non magnetic steel sheet.

The steel box was double walled, the space between the two walls

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

beeing 0,6 cm through which water was flowed at a constant rate.

This cooling system has been proved very succesful ensuring thermal isolation and moderate thermal stability.

The sample was fed constantly with inert gas (Argon) of high purity through a porcelain tube,. The method proved effective in preventing oxidation of the sample.

The primary current which fed the sample was provided by a 6268 B Hewlett- Packard D.C Power supply which had less than 0,03 % plus 2mV total drift for 8 hours following 30 minutes warm up under constant ambient conditions with an accuracy at preselected current values better than - 16.7 mV/A.

The heaters were fed by a PHILIPS PE 4816 power supply, used as a stable current source, continuously adjustable from 0,01 to 3 A, which for the main voltage variations of 10 % has a nominal value of the output current variation less than 1,5 mA and ripple voltage less than 1 mA r.m.s.

The overall sensitivity of the setup was determined to $\pm 3.10^{-8}$V.

The heating elements produced at 400 watts temperatures up to 700° C with no indication that higher temperatures could not be obtained should the experiment call for it.

EXPERIMENTAL RESULTS AND DISCUSSION

In Fig. 2 the Hall effect per unit current density is plotted against magnetic induction at various temperatures up to the Curie point of the alloy.

The calculation of R_0 and R_1 was made by the following method :

Equation (1) may be written in the following manner :

$$E_H = [R_0 B + (R_1 - R_0)\, 4\pi J] \frac{I}{t} \qquad (7)$$

differentiating in respect to B equation (7) holds :

$$\frac{\partial E_H}{\partial B} \frac{t}{I} = R_0 + (R_1 - R_0)\, 4\pi \frac{\partial J}{\partial B} = R_0 + (R_1 - R_0) \left(\frac{\mu - 1}{\mu}\right) \qquad (8)$$

where μ is the differential permeability.

For low fields the differential permeability is much greater than unity and for high fields is considered equal to unity so that $\partial E_H / \partial B$ is constant for these regions.

R_0 is obtained from equation (8) from the high field slope $\partial E_H / \partial B$ assuming $\mu = 1$.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

The slopes of the high and low fields determine quite accurately within a 3% of error the value of R_0 and R_1.

The ordinates of the slope of the low field curve and of the intersection of the two slopes of the high and low fields, give the quantities $(R_1 - R_0)J_s$ and and $R_1 J_s$.

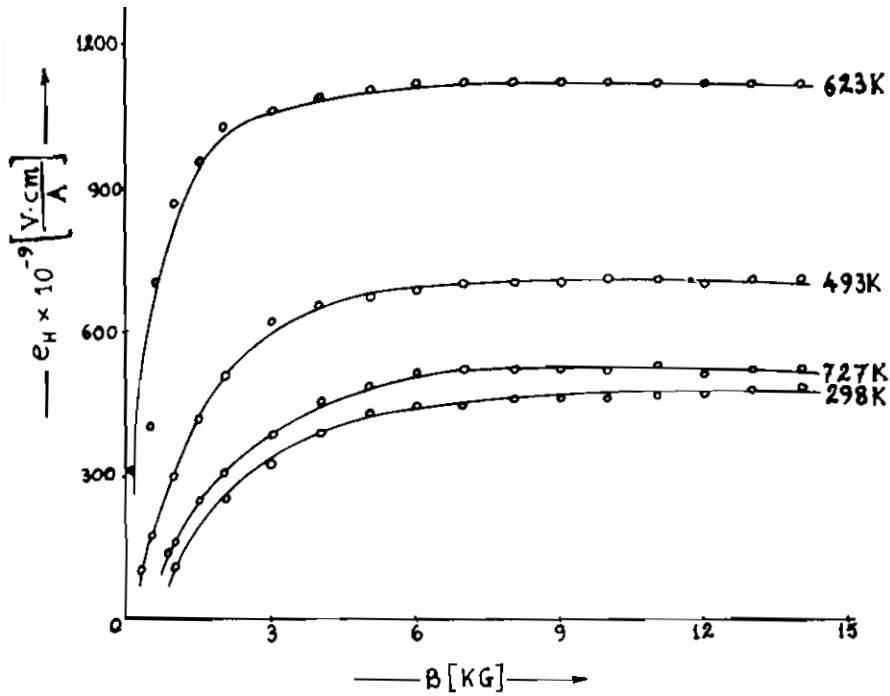

Fig. 2. Hall field per unit current density at various temperatures up to the Curie point

Table I shows the calculated R_0 and R_1, the Hall resistance $\rho_H = 4\pi R_1 J_s$ in $V.cm.A^{-1}$ as well as the saturation magnetization at various temperatures up to the Curie point.

TABLE 1

T°K	R_1	R_0	$4\pi J_s$	ρ_H
298	98,5	-0,42	10,262	101,09
493	221,0	-42,54	9,559	211,264
623	257,0	-50,00	7,335	188,515
727	364,9	-66,90	0,675	11,140

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

R_0 and R_1 are in $V.cm.A^{-1}G^{-1}$ units, the saturation magnetization in 10^3 Gausses and the Hall resistance in $V.cm.A^{-1}$.

According to a method described in (10) the ferromagnetic moment per atom (extrapolated at 0°K) has been estimated to 1,0 μ_B (Bohr magnetons) as well as the $\mu_{Ni} = 0{,}25 \pm 0{,}05$ and $\mu_{Mn} = 3{,}67 \pm 0{,}25\mu_B$ instead of $0{,}3 \pm 0{,}05$ and $3{,}17 \pm 0{,}25$ respectively, which were given by Precy and Morgan (11) who also worked with a composition near 25% Mn at.

The saturation magnetization of the sample thus resulting (816 Gausses.cm^{-3}) differs a little by the value given by the above mentioned authors who gave the value 880 (emu.cm^{-3}).

A plausible explanation for this small difference in saturation magnetization found, may be attributed to the different thermal processing of the samples examined.

Such a dependence has already been reported by (12) and is represented in Fig. 3

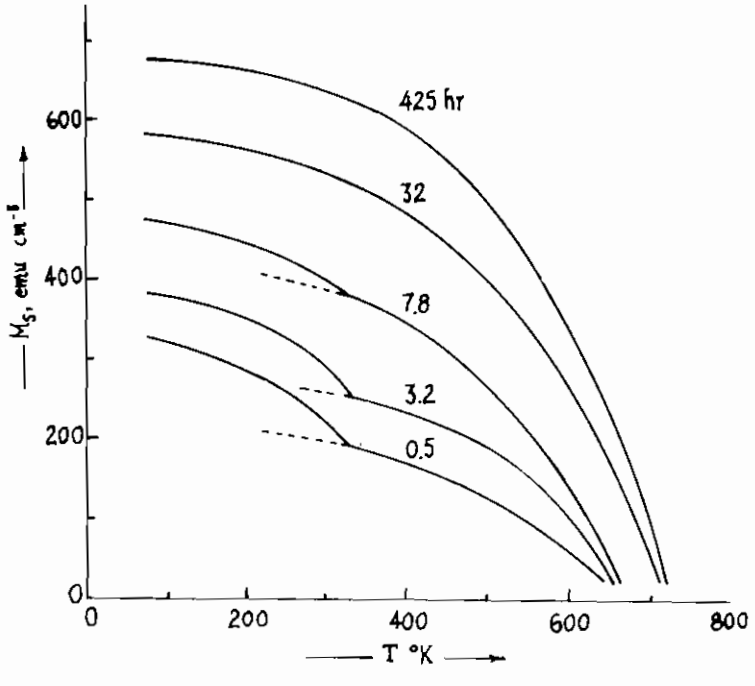

Fig. 3. Variation of the saturation magnetisation with different annealing durations (12).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

showing a profound dependence of the saturation magnetization with various annealing durations.

Fig. 4 shows the variation of the saturation magnetization of the samples at various temperatures.

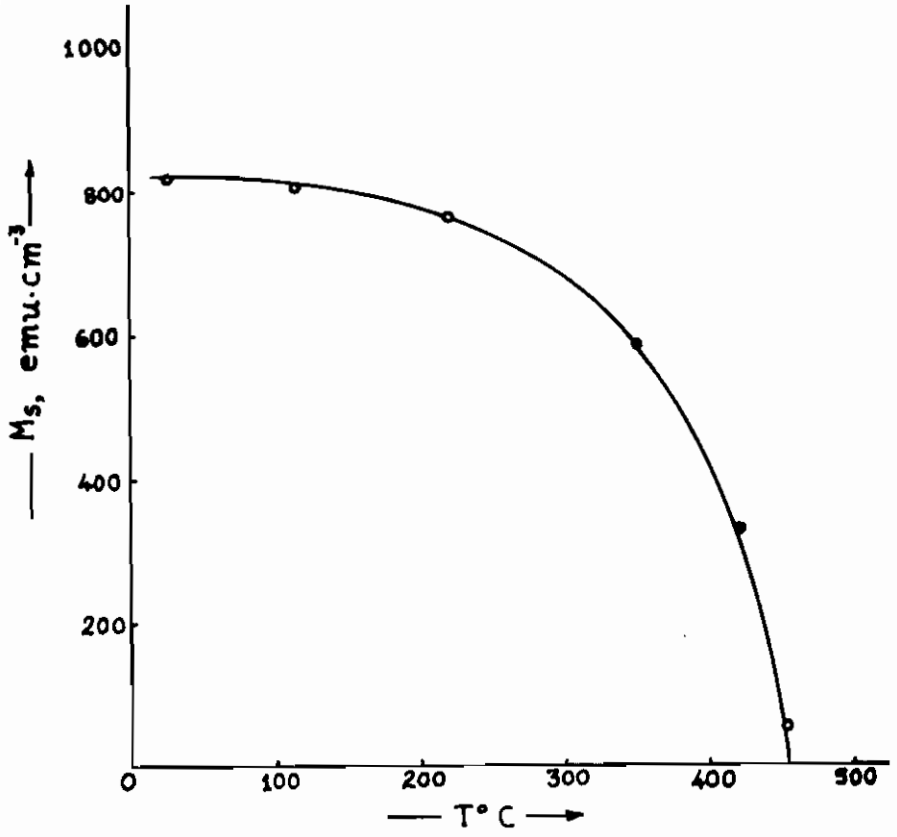

Fig. 4. Saturation magnetization at various up to the Curie point, temperatures

The measurements made on a completely disordered sample, which has been heated to 600°C for 24 hours and then quenched to room temperature has shown that the sample did not saturate at fields as high as 16 KG. Since it is not possible for the atomic moments to vanish, it is reasonable to accept the assumption made by (12) that the moments in disordered Ni_3Mn are not in their totality aligned ferromagneticaly and that some of them lie in opposing directions.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

The exchange interactions between Ni-Ni and Ni-Mn nearest neighbour atoms pairs are supposed to be ferromagnetic but the Mn-Mn pair interactions are antiferromagnetic.

This fact is strongly supported by the way the Curie temperature of the system depends upon constitution of the alloy and for the increase of the Curie point upon ordering.

Finally the number of the effective electrons per atom has been estimated according to relation (4) to 0,62 per atom, which is in close aggrement with the values given by (9).

REFERENCE

1. N. V. Volkenstein - G. V. Fedorof : J.E.T.P. *11*, 48, (1960).
2. Jellinghaus - D. Andres : Annalen d. Physik, *5*, 187, (1960).
3. M. Brittel - E. Pugh : Phys. Review *112*, 1516, (1958).
4. Dutta Roy - Subrahanayam : Phys. Review *177*, 1133, (1969).
5. E. Pugh : Phys. Review *97*, 647, (1955).
6. R. Sondheimer : Proc. Roy. Soc. (London) *A 193*-, 484, (1948).
7. E. Pugh : Phys. Review *97*, 647, (1955).
8. S. Foner - E. Pugh : Phys. Review *109*, 1129, (1955).
9. Ahern - Martin - Sucksmith : Proc. Roy. Soc. (Lohdon) *248*, 145, (1958).
10. Berkowitz - Kneller : Magnetism and Metalurgy, Vol. 2, page 541, Academic Press, 2nd edition N.Y. 1969.
11. Piercy - Morgan : Can. Journal of Physics *31*, 435, (1961).
12. Hahn - Kneller : Z. Metallkund. *49*, 426, (1958).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

ΠΕΡΙΛΗΨΙΣ

ΕΠΙΔΡΑΣΙΣ ΤΗΣ ΘΕΡΜΟΚΡΑΣΙΑΣ ΕΠΙ ΤΟΥ ΦΑΙΝΟΜΕΝΟΥ HALL ΕΙΣ ΤΕΤΑΓΜΕΝΟΝ ΚΡΑΜΑ Ni_3Mn

Ὑπὸ

Ι. Α. ΤΣΟΥΚΑΛΑ καὶ Ε. ΠΑΠΑΔΗΜΗΤΡΑΚΗ - ΧΑΙΧΛΙΑ

(Ἐργαστήριον Ἐκτάκτου Αὐτοτελοῦς Ἕδρας Φυσικῆς Πανεπιστημίου Θεσσαλονίκης)

Εἰς τὴν παροῦσαν ἐργασίαν μελετᾶται τὸ φαινόμενον HALL εἰς τὴν τεταγμένην φάσιν τοῦ σιδηρομαγνητικοῦ κράματος 77 Ni - 23 Mn at % συναρτήσει τῆς θερμοκρασίας καὶ ὑπολογίζεται ἡ μαγνήτισις κόρου τοῦ δείγματος συναρτήσει τῆς θερμοκρασίας ὡς καὶ τὸ πλῆθος τῶν ἐνεργῶν ἠλεκτρονίων ἀγωγιμότητος ἀνὰ ἄτομον.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.