ANTIFERROMAGNETISM OF IRON-NICKEL ALLOYS

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The temperature dependence of the paramagnetic susceptibility of Fe—Ni alloys (5—39 atomic per cent Ni) is investigated. The results obtained for the atomic magnetic moment (P_p) and the paramagnetic Curie point (Θ_p) can be explained by assuming the existence of a negative exchange interaction between the iron atoms in the γ-phase.

1. Up to the present time the temperature dependence of the paramagnetic susceptibility of iron-nickel alloys has been investigated in single-phase alloys of this system.[1-3] As for Invar and other alloys with large iron content, these have practically not been investigated in the paramagnetic region.[4] Yet the investigation of the magnetic properties of these alloys over a wide temperature range is of great interest, since "anomalous" physical properties are observed in Invar alloys.

Until very recently it was customary to explain this by saying that in these alloys the exchange interaction energy between the electrons on neighboring ions changes sharply with expansion and contraction of the crystalline lattice.

Kondorskiĭ and Sedov were the first to show[5-7] that the peculiarities of the physical properties of Invar alloys have an entirely different origin, namely, "latent" antiferromagnetism which arises as a result of negative exchange interaction between the d-electrons of neighboring iron atoms in the face-centered lattice (γ-phase). Kondorskiĭ[6] has calculated that antiferromagnetism in iron-nickel alloys should take place at concentrations of nickel less than 30%.

It was therefore of great interest to investigate iron-nickel alloys having a large iron content in the paramagnetic region ($T \gg \Theta_f$, where Θ_f is the ferromagnetic Curie point). To this end we have studied alloys with the following atomic content of Ni: 4.7, 9.6, 14.4, 19.3, 27, 29, 30.9, 34.9, and 38.8%. Attention was directed principally toward investigating the γ-phase of these alloys. Magnetic susceptibility measurements were made using the Faraday-Sucksmith method over a wide temperature interval, 300 to 1500°K in an inert-gas (argon) atmosphere. The measurements were carried out during increasing temperature.

2. In Fig. 1 we present our data on the dependence of the inverse specific susceptibility ($1/\chi$)

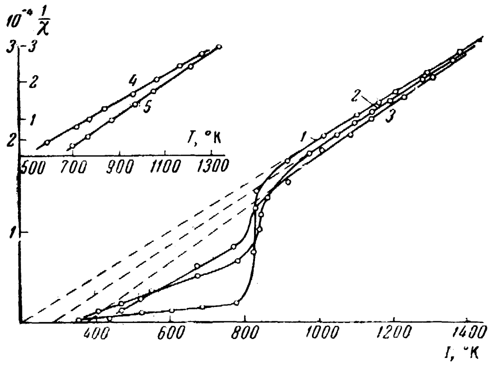

FIG. 1. Temperature dependence of the inverse susceptibility for alloys with the following atomic concentrations of Ni: 1–27%; 2–29%; 3–30.9%; 4–34.9%; 5–38.8%.

on the temperature (T) for Invar-type alloys. It is seen that in the alloys with a Ni content of 27, 29, and 30.9% the dependence of $1/\chi$ on T experiences a jump that corresponds to the structural transition $\alpha \rightleftarrows \gamma$. The sharpest change in susceptibility occurs in the 27% alloy; it takes place at 820°K. For the other two alloys the structural transition is much less obvious and proceeds at a lower temperature. The Curie-Weiss law is followed by both the α-phase and γ-phase of these alloys, but with different values of the Curie-Weiss constant (C) and paramagnetic Curie point (Θ_p).

The magnetic susceptibility of the alloys with 34.9 and 38.8% Ni varies according to the Curie-Weiss law over the entire investigated temperature interval, there being no phase transitions observed (γ-phase). The temperature dependence of the paramagnetic susceptibility of alloys with Ni-content 4.7, 9.6, 14.4, and 19.3% was studied only for the γ-phase (Fig. 2). The variation of $1/\chi$ with T for these alloys is linear.

Using the experimental data, we have determined for the γ-phase of all the investigated alloys the value of the effective magnetic moment

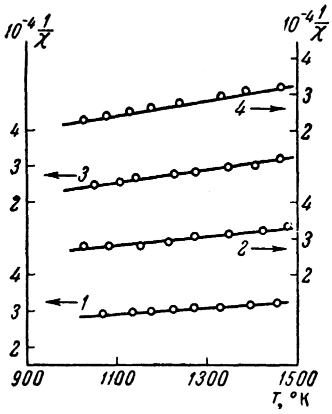

FIG. 2. Temperature dependence of inverse susceptibility for alloys with atomic concentrations of Ni: 1–4.7%; 2–9.6%; 3–14.4%; 4–19.3%.

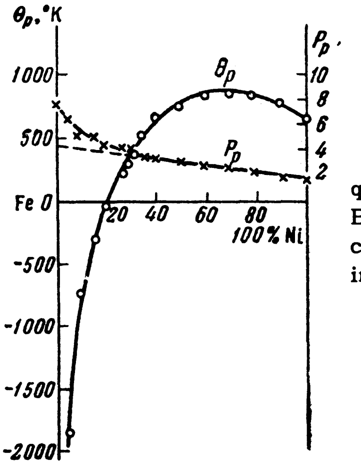

FIG. 3. Dependence of the quantities P_p (crosses) (in Bohr magnetons) and Θ_p (circles) on the percentage of Ni in the alloy.

P_p (in Bohr magnetons) on an atom in the alloy, and also the paramagnetic Curie point Θ_p. The dependence of these quantities on the composition of the alloy is presented in Fig. 3. The values of P_p and Θ_p for alloys containing 50% Ni and higher are taken from previously published work.[3] The magnetic moment of alloys with large Ni content (greater than 50%) varies linearly with composition. In the interval of concentrations 40—50% a deviation from linearity begins to appear, becoming greater at lower concentrations of Ni.

Of special interest is the dependence obtained for the paramagnetic Curie point.

From Fig. 3 it can be seen that the temperature Θ_p is not a linear function of the Ni concentration. Characteristically, near 50% a marked decrease in the magnitude of Θ_p occurs, and in the interval 30—40% Ni a sharp drop in Θ_p is observed. A similar behavior was observed by Kondorskiĭ and his co-workers[7,8] in an investigation of the saturation magnetization and residual resistivity of iron-nickel alloys.

It is extremely interesting that at a concentration of 20% Ni the paramagnetic Curie point changes sign and becomes negative. Thus, the γ-phase of alloys containing less than 20% nickel, as well as the γ-phase of iron, have a negative paramagnetic Curie point. This is probably associated with the fact that with an increase in the iron concentration, as a consequence of the negative exchange interaction between iron atoms in the γ-phase, the number of antiparallel spins is increasing.

It should be noted that upon extrapolating the curves of P_p and Θ_p from the alloy to pure iron, we obtain for γ-iron $P_p = 7.4$ and $\Theta_p = -3000$°K, which agrees satisfactorily with earlier results (see [1,9]). It is seen that the quantities P_p and Θ_p for pure iron have large values. This is probably explained by the limited applicability of the Curie-Weiss law in its usual form. Such a point of view agrees with the results of Sedov[10] on the antiferromagnetism of iron-manganese alloys, for which the quantity Θ_p, as determined from the Curie-Weiss law, has an infinitely large negative value.

3. Thus, we conclude from the results of this investigation that a negative exchange interaction exists in iron-nickel alloys with a nickel concentration of less than 20%.

Our investigations have confirmed the theory of E. I. Kondorskiĭ, according to which antiferromagnetic interactions between the d-electrons of iron atoms in a face-centered lattice are the principal source of the peculiarities in the physical properties of Invar alloys.

In conclusion we thank Prof. E. I. Kondorskiĭ and V. L. Sedov for a complete discussion of the results of the present work and for their valuable comments.

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