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Abstract

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ON THE TEMPERATURE DEPENDENCE OF THE COERCIVE FORCE OF NICKEL AND IRON-NICKEL ALLOYS IN THIN SPECIMENS

(Presented by Academician I. K. Kikoin, 15 X 1957)

A decrease in the thickness of specimens of magnetically soft substances is accompanied by a general deterioration of their magnetic properties. A sign of the deterioration of magnetic properties may be the observed increase in the coercive force. In works ($^{1-3}$) the dependence of the coercive force on the sheet thickness of magnetically soft materials was investigated, and a regular increase in the coercive force with decreasing thickness was found, beginning from a certain "critical" value. This increase in the coercive force was explained by the fact that, when the thickness of the specimens is reduced, the magnetic structure of the ferromagnet changes and the role of closure domains increases (^{2}), but suggestions were also made that the deterioration of magnetic properties with decreasing specimen thickness is caused by other reasons as well: 1) the increasing influence of the surface layer, which has poorer properties than the material as a whole, and 2) the fact that, in the process of annealing in vacuum or in an atmosphere of a neutral gas, a larger amount of gaseous impurities from the surrounding medium (which is never ideal) penetrates into thin specimens than into thick ones (^{3}).

The aim of the present work was to determine whether the character of the temperature dependence of the coercive force changes with a change in sheet thickness, in particular, whether the character of the temperature dependence of the coercive force changes on passing to those thicknesses at which an increase in the coercive force is observed. It could be expected that, if the increase in coercive force is caused by a change in the ratio between the domain width and the sheet thickness, the character of the temperature dependence of the coercive force would change on passing from thick specimens to thin ones. It is known that investigation of the temperature dependence of the coercive force and comparison with the temperature behavior of the quantities K, λ_s, and I_s make it possible to judge the magnetic structure and the nature of the hysteresis

Fig. 1

Figure 1: Fig. 1

mechanism in ferromagnetic materials.

We investigated the temperature dependence of the coercive force of heavily cold-worked and annealed thin-sheet specimens of nickel and binary iron-nickel alloys with 85, 78, and 50% nickel. The measurements were carried out in a solenoid, in an open circuit, on a ballistic setup. The coercive force was determined by the method of withdrawing the specimen from the ballistic coil, which ensured obtaining this quantity with an error of no more than 3%. The temperature interval of the measurements was from -196 to 300°. The thickness d of the rolled sheet materials was: 0.35; 0.2; 0.1; 0.05; 0.02; 0.01; 0.005 mm. The dimensions of the specimens were $160 \times 4 \times d$ mm. The heat treatment for nickel and the alloy with 50% Ni consisted of a 4-hour anneal at 1100° and subsequent slow cooling. The heat treatment of specimens of alloys with 85 to 78% Ni consisted of the same anneal with slow cooling to 600° and subsequent rapid cooling to room temperature.

Measurements of specimens that had undergone only rolling confirmed our assumptions that the possible influence of thickness in this case is masked by a considerable increase in the coercive force caused by internal stresses produced during mechanical treatment: no regular dependence of the magnitude of the coercive force on thickness was found in these specimens.

Fig. 1. Dependence of the coercive force of annealed nickel on specimen thickness at various temperatures;
1 –at $-196°$; 2 –at $+20°$; 3 –at $+100°$;
4 –at $+200°$; 5 –at $+300°$.

The temperature dependence of the coercive force in specimens that had undergone only rolling proved to be approximately the same for all thicknesses. Thus, for specimens of nickel and of an alloy with 78% Ni, at all thicknesses in the interval from room temperature to the Curie points, the coercive force was proportional to $\sqrt{\theta - T}$, where θ is the Curie temperature.

Thus, our data, together with Döring' s conclusion$^{(4)}$ that the magnetostriction values λ_s of nickel are proportional to I_s^2, make it possible to conclude that, in nickel specimens that have undergone rolling, $H_c \sim \lambda_s / I_s$ in that temperature region where $I_s \sim \sqrt{\theta - T}$ (the latter relation, as is known, is always valid in some temperature region below the Curie point). Having no data on the temperature dependence of the magnetostriction of iron-nickel alloys, we could calculate the values of λ_s / I_s for the compositions of interest to us only for room temperatures. Comparison of these values with the corresponding values of H_c for specimens with different nickel contents that had undergone rolling showed that

Figure 2 and Figure 3

Figure 2: Figure 2 and Figure 3

$$H_{c100} : H_{c85} : H_{c78} : H_{c50} = \left(\frac{\lambda_s}{I_s}\right)_{100} : \left(\frac{\lambda_s}{I_s}\right)_{85} : \left(\frac{\lambda_s}{I_s}\right)_{78} : \left(\frac{\lambda_s}{I_s}\right)_{50}, \tag{1}$$

where the subscripts denote the percentage content of nickel in the specimens. (1) shows that the proportionality $H_c \sim \lambda_s/I_s$ also held for the alloy specimens. The existence of such proportionality for specimens having, above room temperature, relatively small values of the magnetic anisotropy constant agrees with the conclusions of Néel' s theory(5) for the case when $\lambda_s \sigma \gg K$, where σ is the mean value of the internal stresses.

After annealing of specimens that had previously been rolled, a regular dependence is observed of the coercive force of specimens of all compositions on the sheet thickness. Figures 1 and 2 show curves of the dependence of H_c on thickness at different temperatures for specimens of nickel and of an alloy with 50% Ni. When the thickness is reduced from 0.35 to 0.1 mm, the coercive force changes only slightly (by 16-25%); further thinning of the sheet leads to a stronger increase in it. Below a certain thickness value (the critical one), a sharp rise in the coercive force is observed. The critical thickness is greater for nickel and for the alloy with 50% Ni than for alloys with 35 and 78% Ni. The temperature dependence of the coercive force of specimens of different thicknesses from 0.1 to 0.005 mm, annealed after rolling, is approximately the same. In the specimen of the alloy with 78% Ni, the character of the temperature dependence of H_c after annealing changed hardly at all, which is evidently connected with the small value of the anisotropy constant for this composition.

Fig. 2. Dependence of the coercive force of an alloy with 50% Ni on specimen thickness at different temperatures.
1 –at −196°; 2 –at +20°; 3 –at +100°; 4 –at +200°; 5 –at +300°.

Fig. 3. Dependence of the coercive force of annealed nickel on temperature. The curve was calculated by formula (2); the points are the measured values.

The temperature dependence of H_c for a nickel specimen after annealing proved to be different. In the temperature interval from −196 to 300°, it, as our measurements showed, is satisfactorily described by the formula:

$$H_c = a\frac{\sqrt{K}}{I_s} + b\frac{\lambda_s}{I_s}, \tag{2}$$

where a and b are constants depending on the sheet thickness and on the method of heat treatment.

Figure 3 presents a curve calculated by formula (2) for $a = 1.23$ and $b = 5 \cdot 10^6$, and also shows points representing the measured values of H_c for a nickel specimen with thickness $d = 0.3$ mm. K and I_s enter the first term of formula (2) in the same powers as they enter the formulas for H_c following from the theory of inclusions ($^{6-8}$) and from theories relating H_c to delays in the growth of nuclei ($^{7-}$).

On the basis of the results obtained, some conclusions may be drawn about the causes of the increase in coercive force observed in annealed specimens.

of the coercive force with decreasing thickness. Ya. S. Shur and V. A. Zaikova showed that the sharp increase in the coercive force in thin sheets of transformer steel (a material with a relatively large magnetic-anisotropy constant) begins when the linear dimensions of the domains become comparable with the sheet thickness. In this case, for relatively large values of the magnetic-anisotropy constants, if the easy-magnetization axes do not lie in the plane of the sheet, the magnetic moments of the domains at $I < I_s$ likewise will not lie in this plane. In thin sheets this leads to the appearance of magnetic charges on the surface of the sheet and ultimately to a retardation of the remagnetization process and an increase in the coercive force.

In specimens with a relatively small magnetic-anisotropy constant, the magnetic moments of the domains are more readily oriented in the plane of the sheet. In this case the principal cause producing a retardation of the magnetization process in thin sheets will be, as in thick ones, the inhomogeneity of the structure of the material. However, in thin sheets impurities penetrating from the gaseous medium during annealing may, other conditions being equal, occur in larger amounts. Examples in which this circumstance is the cause of the increase in coercive force in thin sheets are given in (^{3}).

In the present work alloys of the same type as in (^{3}), i.e., alloys with a relatively small anisotropy constant, were studied; therefore in all cases, with the exception of nickel, at low temperatures it was to be expected that the difference between the coercive force in thin and thick sheets was due mainly to technological causes. The observation in our specimens of the same temperature dependence of H_c for all thicknesses (from 0.1 to 0.005 mm) confirms this assumption.

The results obtained in the present investigation thus make it possible to assert that the increase in H_c when the sheet thickness is reduced to 0.005 mm in materials with relatively small values of the anisotropy constant is due chiefly to the influence of impurities penetrating into the sheets during processing; consequently, in these materials, with improved processing conditions, it is possible to obtain higher values of magnetic permeability and a reduction in the coercive force. The "irreparable" deterioration of magnetic properties associated with the influence of domain structure in materials similar to permalloy, with a low value of the anisotropy constant, occurs at thicknesses smaller than 0.005 mm.

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