For high accuracy a) select $r_1 \approx 2$; b) try for $\delta_\alpha = 0$ and a possibly lower value of G.

If ρ is known, this method permits determination of the viscosities η and η_r. If the friction moment of the inner cylinder is measured in addition, ρ, η, and η_r can be found. A certain increase in the measurement accuracy can be achieved by rotating the magnetic field; however, the difficulty in realizing a field rotating according to a given law apparently makes such constructions without promise.

NOTATION

η, shear viscosity; η_r, rotational viscosity; R_1, R_2, radii of the inner and outer cylinders; t, running time; ρ, density; Ω_2^0, characteristic value of the angular velocity of the outer cylinder; S, surface area of the inner cylinder; I, moment of inertia of the inner cylinder; α, friction coefficient under the condition that the friction moment in the supports is proportional to the velocity of axis rotation; Ω_1, angular velocity of the inner cylinder; $\Gamma = R_1/R_2$; and τ, dimensionless time.

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MAGNETIC RELAXATION OF ELECTROTECHNICAL STEEL IN CONSTANT MAGNETIZING FIELDS AT VARIOUS TEMPERATURES

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Experimental studies are performed of magnetic relaxation in specimens of electrotechnical steel in weak constant magnetizing fields at room and liquid nitrogen temperature.

Experimental studies have shown that the magnetic properties of ferromagnets vary with time [1-8]. Time dependence of magnetic properties can be observed in both quasistatic magnetization and in magnetization in ac fields. Time effects in ferromagnets having a domain structure are caused by the fact that upon change in the external magnetic field H thermodynamic equilibrium in the domains is established only after a certain time period, due to a lag in the magnetization J with respect to the field. This thermodynamic equilibrium (magnetic relaxation) sets in because of interaction of spin waves (magnons) among themselves, and also with phonons, dislocations, impurity atoms, and other crytalline microdefects. The following may be potential sources of time effects in ferromagnets undergoing remagnetization: motion of dislocations and their Cuttler shells produced by magnetostriction stresses [9]; impurity atom diffusion; local heat liberation due to displacement of interdomain boundaries, which leads to localization of thermal stresses.

Study of time effects caused by relaxation processes in ferromagnets is of theoretical importance, since it clarifies the nature of all the various processes occurring during remagnetization, and of practical value as well, in connection with determination of magnetic

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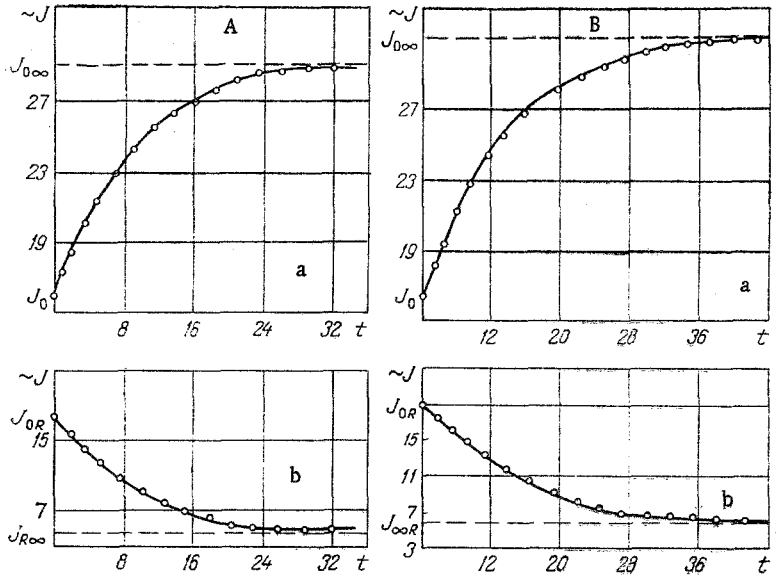

Fig. 1. Change in viscous magnetization of electrotechnical steel specimen for application (*a*, $H \to H_m$) and removal (b, $H_m \to 0$) of weak magnetic field at room (A) and liquid nitrogen (B) temperatures. Time t, sec.

characteristics of materials and definition of their role in overall electromagnetic loss formation. At the present time a government standard 802-58 [10] has been introduced, according to which measurement of magnetic properties must be performed with consideration of the time required for relaxation processes. The problem of comprehensive study of the physical properties of iron-based electrotechnical silicon steels is of great practical importance, due to the intense development of electrical technology, radio/electronics, and other new technological areas which require increased production of these steels. Therefore, in studying all physical processes which occur in ferromagnets during remagnetization, an important role is played by relaxation processes, which produce a definite contribution to total electromagnetic losses.

The present study will investigate magnetic relaxation in electrotechnical steel in constant magnetizing fields at room and liquid nitrogen temperatures. Time effects related to retardation of the magnetization with respect to the applied field H during establishment of thermodynamic equilibrium have been termed magnetic aftereffect or magnetic viscosity. The time required for establishment of the magnetization may range from 10^{-9} sec to tens of minutes, hours, or even days.

Depending on magnetization conditions, temperature, ferromagnet structure, and other factors, several types of magnetic viscosity can be distinguished. The first type can be observed during aperiodic change of the applied magnetic field H close in value to the coercive force. In these fields an increase in magnetization is usually produced by irreversible shift of interdomain boundaries, and settling time τ for the new magnetic state is proportional to the differential magnetic permittivity $\varkappa_d$ and inversely proportional to absolute temperature T [2]:

$$\tau = A \frac{\varkappa_d}{T}. \qquad (1)$$

The second type of magnetic viscosity is caused by impurity atom diffusion. The diffusion process has an effect on the free energy of interdomain boundaries, and thus, on the settling time of the new magnetic state during remagnetization.

The third type of viscosity is characterized by a quite long relaxation time, several minutes or more. This type of magnetic viscosity is observed in high coercivity alloys and has been termed superviscosity [11]. In this case an important role is played by thermal energy fluctuations, which encourage remagnetization of domains and establishment of the equilibrium state.

The fourth type of viscosity is caused by electron diffusion between ions of bi- and trivalent iron, and is found mainly in ferrites. This process is analogous to diffusion of ions themselves, but occurs much more easily, so that ferrites are characterized by a low magnetic viscosity.

A fifth type is observed when magnetization is changed not by a shift in domain boundaries, but only by rotation of the electron spin magnetic moment vector. This type occurs in ferrites and mainly in thin ferromagnetic films. The remagnetization times are of the order of 10^{-9} sec.

Magnetic viscosity manifests itself especially intensely in magnetically soft materials in weak fields, where the change in magnetization is produced by shift of interdomain boundaries.

During the relaxation process the macroscopic physical properties asymptotically approach their new equilibrium values. Under certain conditions a number of processes can occur within a solid:

1) relaxation of stresses $\sigma=\varphi(t)_\varepsilon$ characterizing the change in stress with time at a fixed value of deformation ε = const;

2) relaxation of deformations $\varepsilon = \Phi(t)_\sigma$ at constant stress σ = const, the so-called creep phenomenon;

3) $\Delta P = \psi(t)_E$, a change in polarization characterizes relaxation in dielectrics at a constant value electrical field intensity E = const;

4) change in magnetization with time $\Delta J = f(t)_H$ at constant magnetic field H = const characterizes magnetic relaxation.

We will attempt to formulate an expression for the viscous change in magnetization produced by magnetorelaxation processes. In all stages of remagnetization of a ferromagnet when a magnetizing field $H \to H_m$ is applied, due to the magnetic aftereffect phenomenon, the specimen magnetization takes on an equilibrium value after some period of time t. With increase in t the increment in magnetization increases ($\Delta J > 0$), while on the other hand, upon switch-off of the field $H_m \to 0$ the increment in residual magnetism decreases, i.e., $\Delta J_R < 0$. The values of ΔJ and ΔJ_R, the spontaneous increments in establishing thermodynamic equilibrium, have been termed the viscous component of the magnetization. The changes in magnetization components upon application and removal of a magnetizing field for initial magnetization and along the hysteresis loop have been explained thoroughly in [6]. Upon field application $H \to H_m$, after a very short but finite time the magnetization changes to J_o, while in the presence of magnetic viscosity, the time over which the magnetization reaches its limiting value $J_{o\infty}$, is significantly longer, and theoretically $t \to \infty$.

In practice, for a given magnetic field H the limiting magnetization $J_{o\infty}$ is reached in different ferromagnets at different finite times t.

Experimental studies of magnetic relaxation were performed on specimens of electrotechnical steel containing 3% silicon, using the technique described in [7]. To bring them to an equilibrium state the specimens were vacuum annealed at 900°C. The vacuum level was controlled so that practically no oxidation of the specimen surface occurred. Special magnetometric equipment permitted taking relaxation curves of specimens at both room and liquid nitrogen temperatures. Experimental results in the form of $J = f(t)$ curves, characterizing the viscous change in magnetic properties with time at room temperature for application and removal of a weak magnetic field H are shown in Fig. 1A (a, b).

It follows from examination of the data that the viscous change in magnetization of electrotechnical steel specimens in weak magnetic fields takes place over the course of a finite time. It follows from Fig. 1A (a) that at room temperature this time comprises 28-30 sec for the specimens studied. Relaxation processes are practically completed over this time period and the magnetization reaches its limiting steady-state value. A similar amount of time is required to reestablish thermodynamic equilibrium when the constant magnetizing field is switched off (Fig. 1A (b)). It also follows from these curves that the relaxation processes proceed more intensely in the initial time interval, and then at some point their speed decreases and the viscous change in magnetization becomes practically insignificant, the steady-state values $J_{o\infty}$ and $J_{\infty R}$ being reached. As was shown in [6], the experimental $J = f(t)$ curves can be described by the equation

$$J = J_0 + (J_{0\infty} - J_0)\left(1 - e^{-\frac{t}{\tau_H}}\right) \quad (2)$$

for field application $H \to H_m$ and

$$J = J_{\infty R} + (J_{0R} - J_{\infty R})\, e^{-\frac{t}{\tau_H}} \quad (3)$$

for field removal $H_m \to 0$.

Similar studies were performed at liquid nitrogen temperature. Results for application and removal of a weak magnetizing field H are shown in Fig. 1B (a, b). It is evident from the figure that the time required to attain the limiting magnetization values $J_{0\infty}$, $J_{\infty R}$ increases in comparison to room temperature values, comprising 38-42 sec. It can be seen that at lower temperatures the time for establishment of complete thermodynamic equilibrium increases by 10-12 sec as compared to room temperature. These results also confirm the first rule of viscosity [2], which states that in weak magnetic fields the time required for relaxation processes is inversely proportional to absolute temperature, and thus increases with decrease in temperature. It is natural to assume that this increase in relaxation time with reduction in temperature is related first, to a decrease in random thermal energy fluctuations, required to overcome energy barriers in domain transitions from metastable to stable equilibrium state, and second, to retardation of all those diffusion processes and stress relaxation which have an effect on the viscous change in magnetization upon establishment of thermodynamic equilibrium.

Thus, it has been experimentally established that the time required for relaxation processes in establishing thermodynamic equilibrium in electrotechnical steel with 3% silicon content in weak magnetizing fields at room temperature is approximately 28-30 sec, increasing to 38-42 sec at liquid nitrogen temperature.

The results obtained are of practical interest in connection with the wide use of electrotechnical steel in various areas of technology, and are also of theoretical interest in the continuing study of remagnetization processes and the role of relaxation in formation of total electromagnetic losses.

NOTATION

t, time; T, temperature; A, proportionality coefficient; σ, stress; ε, relative deformation; J, magnetization; H, magnetic field intensity; E, electric field intensity; P, polarization vector; τ_H, mean parameter characterizing relaxation time.

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