EFFECT OF MAGNETIC VISCOSITY ON THE FREQUENCY PROPERTIES OF FERRITES

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The magnetic viscosity of a series of nickel-zinc ferrites has been studied under conditions of free and of forced variation of magnetization. For the first time, the viscosity properties have been measured by both methods on the same specimens. An estimate is made of the viscous friction constant.

THE effect of magnetic viscosity in metallic and semiconducting ferromagnetics is ordinarily studied by two different methods: (1) under conditions of free variation of the magnetization (aperiodic conditions), and (2) under conditions of forced magnetization (periodic conditions, sinusoidal field with frequency f). No systematic experimental comparison of data obtained by these different methods has hitherto been carried out.

1. In 1928, Arkad'ev gave a theory of the effect of magnetic viscosity on the frequency properties of ferromagnetics.[1] If a ferromagnetic possesses magnetic viscosity, i.e., if in response to a suddenly altered field $H + \Delta H$ the magnetization of the material changes according to

$$\Delta I = I_1 + I_2(1 - e^{-t/\tau}), \tag{1}$$

then upon application of a sinusoidal alternating magnetic field, with amplitude H_0 and frequency f, the complex permeability $\mu' = \mu - i\rho'$ will depend on frequency in accordance with the following relaxational formulas:

$$\mu = \mu_0 + m_1 / [1 + (f/f_u)^2]; \tag{2}$$

$$\rho' = \rho'_h + m_1 f / [1 + (f/f_u)^2], \tag{3}$$

where

$$f_u = 1/2\pi\tau. \tag{4}$$

Here μ_0 is the conservative or elastic permeability of the material at very high frequency, ρ'_h is the "viscous" permeability due to hysteresis, $m_1 = 4\pi I_2/\Delta H$, f_u is a critical frequency at which ρ' reaches its maximum, and τ is the relaxation time that appears in (1). As has been shown by one of us,[2] the relaxation time τ, which describes the magnetic viscosity of the material, is at constant temperature directly proportional to the differential susceptibility in the final state of the ferromagnetic (the first law of magnetic viscosity),

$$\tau = A\chi_d(H), \tag{5}$$

where A is a constant, independent of the field H. Consequently the critical frequency according to (4) will be

$$f_u = 1/2\pi A\chi_d(H). \tag{6}$$

Becker[3] calculated the damping effect of microscopic eddy currents for metallic ferromagnetics. In weak fields, where the dominant process is reversible displacement of the walls between domains, the frequency dependence of the initial permeability, according to Becker, is of relaxational character, since this author neglects the effect of wall "inertia". The relaxation frequency in this case is inversely proportional to the friction constant Ω, which is determined chiefly by the electrical conductivity of the ferromagnetic. The relaxation frequency is furthermore inversely proportional to the initial susceptibility. Consequently the relaxation time for magnetization of a metallic ferromagnetic in a weak field is directly proportional to the product $\Omega\chi_a$. From Becker's work it follows that

$$\tau = (\Omega l / 3I_s)\chi_a. \tag{7}$$

No. of specimen	Chemical composition mol %		t° Sintering temperature °C	Static data					Aperiodic conditions		Frequency properties	
	$NiOFe_2O_3$	$ZnOFe_2O_3$		μ_a, G/Oe	I_s, G	H_c, mOe	ρ, Ω·cm	χ_d max, G/Oe	τ_{max}, μsec	τ/χ_{jump}, sec Oe/G	ΩS, Oe sec	h_0, mOe
1	15.3	34.7	1350	1700	160	70	$3\cdot10^5$	1150	20	$2.7\cdot10^{-8}$	$3.2\cdot10^{-6}$	35
2	17.4	32.6	1275	1250	125	130	$4\cdot10^5$	340	7	$3.3\cdot10^{-8}$	$0.9\cdot10^{-6}$	85
3	17.4	32.6	1320	1900	160	85	$0.2\cdot10^5$	880	25	$4\cdot10^{-8}$	$1.9\cdot10^{-6}$	60
4	17.4	32.6	1375	2250	160	50	$0.9\cdot10^4$	1140	40	$4.3\cdot10^{-8}$	$2.2\cdot10^{-6}$	45
5	17.4	32.6	1400	2920	180	60	$0.2\cdot10^5$	830	21	$4.3\cdot10^{-8}$	$1.4\cdot10^{-6}$	40

Becker[3] also calculated a critical frequency for irreversible jumps, likewise brought about by the presence of magnetic friction. Let the mean jump distance of a wall, for quasi-static magnetization, be S ($S \leq \ell \sim 10^{-4}$ cm); and let the mean value of the critical field, below which jumps are impossible, be h_0. Then the jump speed v in average fields conforms to the known law

$$\Omega v = H - h_0. \tag{8}$$

The distance S is traversed by a wall in time $\tau' = S\Omega/(H - h_0)$. Therefore Becker estimates the critical frequency for such irreversible jumps as

$$\omega_{cr} = (H - h_0)/\Omega S. \tag{9}$$

For frequencies exceeding ω_{cr}, a wall executing a jump does not have time to traverse the full distance S during a half period; therefore the permeability decreases with increasing frequency.

Numerous experiments on the study of magnetic viscosity under conditions of free magnetization, conducted in our laboratory, have shown that large magnetic viscosity is observed precisely in the range of irreversible jumps, that is in average fields. In weak and very strong fields, the magnetic viscosity is appreciably smaller. The nature of the time dependence of the magnetization in average fields has been insufficiently investigated theoretically. At present there are only the formal activation theory of Street and Woolley (1948) and the fluctuation theory of Néel (1951) for the time dependence of magnetization in this range of fields.

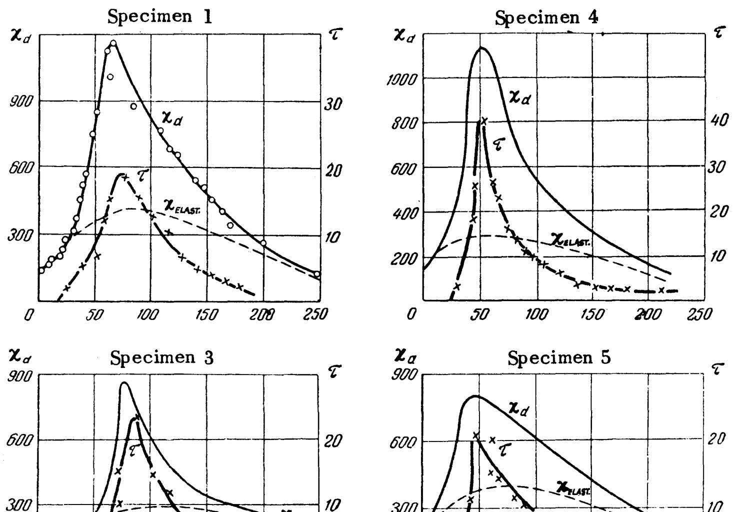

FIG. 1. Dependence of relaxation time τ (μ sec) and of differential susceptibility χ_d on magnetic field (mOe). The dashed curve is the elastic component of the susceptibility, χ_{elast}.

If viscosity is especially large in the range where hysteresis most clearly exhibits itself, then probably both phenomena (hysteresis and magnetic viscosity) are of the same nature. Kondorskii[4] established that the shape of the hysteresis curve of a polycrystalline ferromagnetic is determined by the magnetic interaction of the crystallites or domains. Such magnetic interaction explains the mode of dependence of the differential irreversible-jump susceptibility upon the external field. Apparently a calculation of the magnetic interaction of the particles can give a definite correlation between the friction constant and the magnetic viscosity, which is proportional to the differential jump susceptibility.

2. We have performed experiments with the object of observing the effect of the magnetic viscosity of ferrites on their frequency properties. Five toroidal specimens of nickel-zinc ferrites were studied; their compositions, sintering temperatures (the sintering lasted four hours), and magnetic properties are given in the table. The measurement of magnetic viscosity was carried out by a method that was developed by Telesnin and Lednev[5] and that uses a pulsed oscillograph. The measurements were made by symmetric pulsed magnetization reversal of the specimen from $+H_0$ to $-H_0$. Such conditions are convenient for comparison with frequency data. Just as in Ref. 5,

large magnetic viscosity was observed only in the range of irreversible jumps. The emf vs time curve could be approximated with an exponential.

Curves that show the dependence of the relaxation time τ, characteristic of the magnetic viscosity, on the magnetic field H_0 are given in Fig. 1. The results of the experiments at room temperature show that (5) is well satisfied on all the specimens, provided χ_d is interpreted as the irreversible component χ_{jump} of the susceptibility, corresponding to magnetization not by elastic displacement, but by sudden jumps ("jump" in the subscript) of walls from one position to another.

The total differential susceptibility, measured by the usual ballistic method, consists of two components — the elastic susceptibility χ_{elast} (shown in dashes in Fig. 1), and the jump susceptibility χ_{jump} — so that $\chi_d = \chi_{elast} + \chi_{jump}$. Such an analysis of the susceptibility corresponds to Arkad'ev's expression (1), in which the change of magnetization is separated into a "rapid" and a "viscous" part. In weak fields (less than the critical field h_0), where there are no jumps, the magnetic viscosity is negligible (less than 1 μsec), though the initial susceptibility is very large ($\chi_a \sim 200$).

The values of the constant $\tau/\chi_{jump} = A$ for all the specimens, at room temperature, are given in the table. Also given are the maximum values of χ_d and τ.

As can be seen from Fig. 1, the critical frequencies (4), $f_u \sim 1/\tau$, should decrease rapidly upon change of the field H_0 and should lie in the interval 1.5 to 15 kcs, i.e. in the audio range. Therefore an investigation with sinusoidal fields was carried out in the range 400 cps to 60 kcs.

The permeabilities μ and ρ' were determined by means of a differential transformer; one of its arms contained the specimen, and the other contained a standard resistance R and inductance L. To decrease the effect of harmonics, additional resistance was inserted in the arms, and the measurement circuit of the bridge contained a filter and a selective amplifier. Since skin effect is absent in ferrites, the permeabilities were determined by the formulas

$$\mu = L/L_0, \quad \rho' = \Delta R/2\pi f L_0, \tag{10}$$

where L_0 is the inductance of the empty winding of the specimen, and R is the effective resistance due to losses in the core. Figs. 2 and 3 show the dependence of μ and ρ' on frequency for specimen 3, at constant amplitude of the magnetic field H_0. Similar dependence was found for all five specimens. In all cases with $H_0 > h_0$ (jumps occurring), the frequency dependence of ρ' shows a maximum at some frequency f_{cr}.

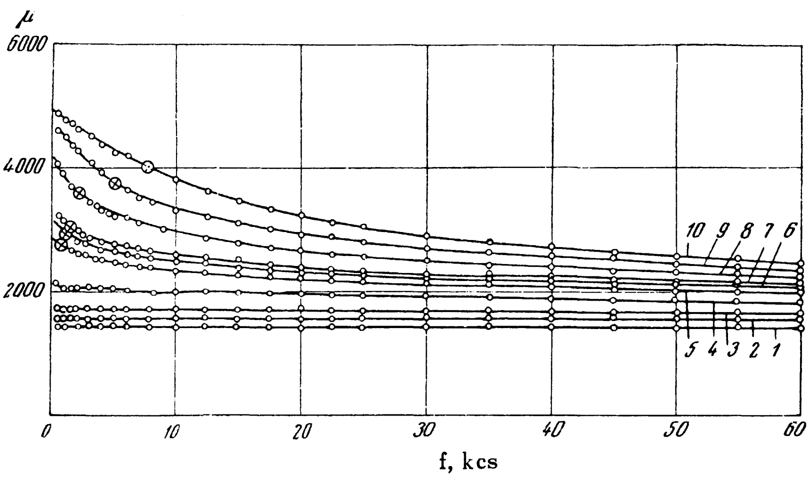

FIG. 2. Dependence of the real part of the magnetic permeability of specimen no. 3 on frequency at constant amplitude H_0 of the magnetic field. The values of H_0 (in millioersteds) for the various curves are: 1, 9; 2, 22; 3, 36; 4, 56; 5, 66; 6, 72; 7, 78; 8, 94; 9, 120; 10, 150.

In Fig. 2 it is clearly evident that the permeability $\mu \sim B/H$ consists of two components: an elastic component that varies only slightly with frequency in this range, and a jump permeability with an evident relaxational dependence on frequency. The circled crosses mark the permeabilities at the critical frequency. The dependence of the critical frequencies f_{cr} on the amplitude of the magnetic field (cf. Fig. 4) was quite different from (6). Instead of $f_u \sim 1/\tau$ we have a linear increase of f_{cr} with field H_0. This kind of dependence can be explained within the framework of Becker's theory. From the graphs it is easy to find the values of h_0, which determine the critical field and the quantity ΩS determined by (9). The corresponding values are given in the table.

The frequency dependence of the permeability of our specimens shows that on increase of frequency in the audio range, the irreversible jumps responsible for magnetic viscosity are suppressed because of magnetic friction, in accordance with (9), even before attainment of the frequencies (4). The calculated condition for observation of relaxation at frequency f_u follows from a comparison of (9) and (4):

$$(H_0 - h_0)/\Omega S > 1/\tau \quad \text{or} \quad (H - h_0)\,\chi_{jump}\,(H_0) > \Omega S/A. \tag{11}$$

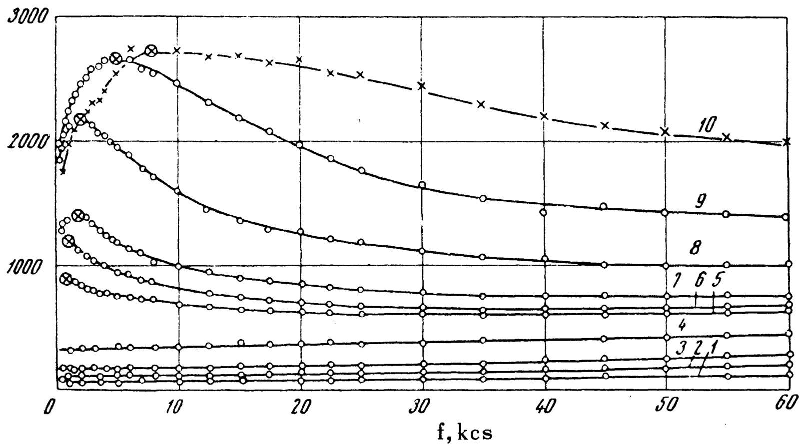

FIG. 3. Dependence of the imaginary part of the magnetic permeability of specimen no. 3 on the frequency at constant amplitude of the magnetic field H_0. The notation is the same as in Fig. 2.

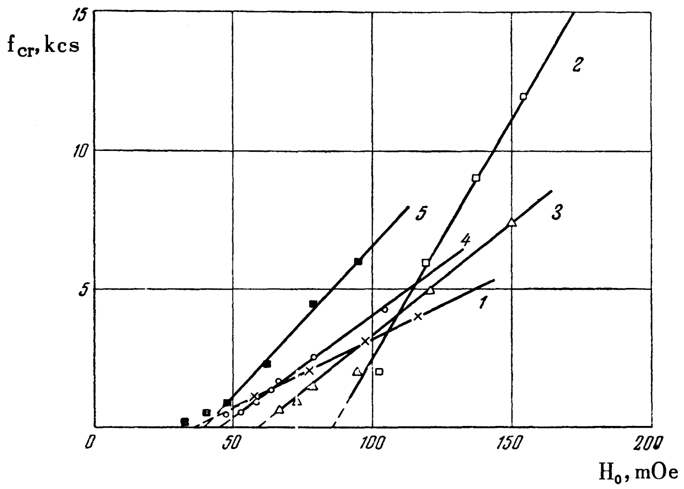

FIG. 4. Dependence of the critical frequencies on H_0 for specimens nos. 1 to 5 (curves 1 to 5 respectively).

In the case of our specimens, condition (11) is not fulfilled. Unfortunately, it is not possible to determine Ω or S separately from our experiments. However, if we take $S \sim 10^{-4}$ cm, then our data permit estimation of the friction constant Ω; it was very high, $\sim 3 \times 10^{-2}$ oersted-sec/cm. This is apparently to be attributed to the approximate character of the relation (9). Further study of the temperature dependence of magnetic viscosity and of the frequency properties in average fields can contribute to the elucidation of the nature of magnetic friction in ferrites.

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