

MAGNETIC RELAXATION IN CONSTANT MAGNETIC FIELDS

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The paper presents the concept of magnetic field effective value, which allows magnetic relaxation to be described without the use of the fictional field of thermal fluctuations devised by Néel. A formal theory has been constructed, which provides an explanation of the relation between magnetic relaxation and magnetic field, temperature and time for various magnetization reversal mechanisms and various types of magnetic substances (*i.e.* weakly and strongly magnetic).

An experimental method of determining the pre-exponential constant τ_0 in the formula for relaxation time is described. The order of magnitude of τ_0 has been evaluated from experimental data for reversal of magnetization by rotations and domain wall movements. The convergence of results indicates that the various magnetization reversal processes take place by the same mechanism, presumably by the activation of spin waves.

1. Introduction

Most magnetic materials feature magnetic relaxation, *i. e.* there are changes in the magnetic moment of a sample in time. The quantity that is measured in experiment is the change in sample magnetization in time counted from the instant a constant magnetic field H is applied to the sample,

$$\left(\frac{\Delta I}{\Delta f(t)} \right) = S_H \quad (1)$$

where $f(t)$ is chosen in such a way that S_H remains constant throughout the measurement. Research is also extensively carried out on the relation between this quantity and other magnetic quantities characterizing the sample, its material constants and its internal structure.

When describing the relaxation process it is assumed that it is due to thermal fluctuations of the magnetic moments of microregions in the sample. Under the term "microregion" we understand here a singledomain magnetic particle in the case of a substance

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of high magnetic phase dispersion or a part of a magnetic domain bound by lattice defects in the case of magnetically homogeneous substances with distinct domain structure [10]. In general terms we assume that the relaxation time of a microregion is given by the formula

$$\tau = \tau_0 \exp [E(H)/kT]. \quad (2)$$

This relation had been derived for the thermal relaxation of small ferromagnetic particles by Néel [14] and Brown [4], who also found τ_0 to be of the order of 10^{-8} s. It is now generally assumed that the value of τ_0 depends on the mechanism by which the magnetic moment vector transits from one energy state to another (by rotation or domain wall movement).

$E(H)$ is the energy barrier which the magnetic moment vector of the microregion must overcome when transiting from state 1 (prior to magnetization reversal) to state 2 (after magnetization reversal).

As is shown here, the character of the relation between time and changes in magnetization (*i. e.* the shape of the function $f(t)$ in Eq. (1)) depends on the form of the energy barrier assumed in Eq. (2).

The following relation is seen to hold true in experiments:

$$S_H = - \left(\frac{\Delta I}{\Delta \ln t} \right) = \text{const } (t). \quad (3)$$

Street and Woolley [18] measured the value of the quantity $S_v = S_H \chi_{\text{irr}}$ along the hysteresis loop. In their method t and ΔI are measured from the instant the field abruptly changes from $H + \Delta H$ to H (the field H , being inverse relative to the saturating field applied earlier, is negative, and $\Delta H > 0$). χ_{irr} is the irreversible susceptibility measured in the field H . The magnitude of S_v proved to be almost constant in the second quarter of the hysteresis loop and has been determined for a number of magnetic substances; they have been accumulated in the work of Brissonneau [3].

Néel [15] interpreted these results on the basis of the model of Preisach [16]. The directions of magnetization of the various microregions fluctuate thermally, giving in their neighbourhood a randomly alternating magnetic field. Néel averaged these fields by introducing for the entire sample a single randomly alternating field of amplitude described by the formula

$$H_T(t) = S'_v(Q + \ln t). \quad (4)$$

The time t is counted each time from any abrupt change in the sample's external field, whereas S'_v is a material constant.

Also, Néel proved (also see [11]) that this field together with Preisach's diagram describes magnetic relaxation in conformity with the results of Street and Woolley, with $S'_v = S_v$. According to Ref. [15], the constant S_v is proportional to $(T/V)^{1/2}$, V —volume of microregion.

The experimental data for many substance do not converge with this result. An $S_v \sim T$ relation is frequently encountered. Street and Woolley [18] obtained such a result

for Alnico, Stierstadt [17] for Ni at a temperature of -273°C to -100°C , Courvoisier [5] for steel, and Taoka [20] for Ni_3Mn .

The present work is an attempt to explain this diversity of results.

2. The concept of magnetic field effective value for various energy barriers

This section deals with the consequences stemming from the form of the external field dependence of the energy barrier in Eq. (2).

In the reversal of magnetization of 180° domain walls by a field parallel to the wall boundaries holds the formula

$$E(H) = 2VI_s(H_0 - H) \quad (5a)$$

where V is the volume of the microregion, I_s is saturation magnetization, H_0 is coercive force of the domain wall without thermal excitation and H is the magnetic field inverse to the saturating field applied earlier.

When small particles, whose easy axes are parallel to the magnetic field, have their magnetization reversed the energy barrier is [2]

$$E(H) = K_u V(1 - h)^2 \quad (5b)$$

where K_u is the uniaxial anisotropy constant (assumed to be positive), and $h = H / \frac{2K_u}{I_s}$ is reduced field.

As numerical calculations have shown [13], in the magnetization reversal of small particles with chaotically distributed easy axes ($K_u > 0$) we have

$$E(H) = K_u V - \frac{1}{c} VI_s H = \frac{VI_s}{c} \left(c \frac{K_u}{I_s} - H \right) \quad (5c)$$

where $c \cong 0.86$.

When magnetostatic energy is taken into account [15], the energy barrier in the case of small particles becomes

$$E(H) = \frac{3}{8\pi} V(H_m - H)^2 \quad (5d)$$

From formulae (5a, b, c and d) it is evident that there are used two forms of energy barriers for negative fields, viz.,

$$\text{a) linear: } E(H) = L(H_0 - H) \quad (6a)$$

$$\text{b) quadratic: } E(H) = S(H_0 - H)^2 \quad (6b)$$

It is also seen that in the case of relaxation in weak inverse fields ($H \ll H_0$) the barriers of type (6b) convert into linear barriers (6a). The quantities L , S and H_0 can be determined from Eqs (6) and (5).

From formulae (6a) and (2), after putting $\tau = t$ (t being the time of action of field H), we find a relation which is the condition for a microregion to have its magnetization reversed

within time t in a given field H

$$H = H_0 - \frac{kT}{L} \ln t/\tau_0 = H_c(t, T) \quad (7)$$

where $H_c(t, T)$ — coercive force when thermal excitation is present. Whence

$$H_{\text{eff}}(t, T) = H + \frac{kT}{L} \ln t/\tau_0 = H_0. \quad (8)$$

The condition of magnetization reversal, Eq. (8), is equivalent to the ascertainment that reversal occurs when the effective value H_{eff} of the applied magnetic field H is equal to the coercive force of the microregion, H_0 . It is an easy matter to conclude that the formula

$$H_{\text{eff}}(t, T) = H + \frac{kT}{L} \ln t/\tau_0 \quad (9)$$

is valid for an arbitrary field H , *i. e.* not only for those which satisfy condition (8). The intuitive meaning of formula (9) is as follows. It is possible to so choose the times t during which different fields H are applied inversely to the sample's magnetic moment that an identical value of H_{eff} is achieved, *i. e.* to achieve an identical probability of magnetization reversal due to the action of these fields. Therefore, the effective value of the magnetic field H , given by Eq. (9), is a measure of the efficiency of its action during the time t it is applied.

Quite analogous reasoning in the case of the quadratic barrier of energy leads to the formula

$$H_{\text{eff}}(t, T) = H + \sqrt{\frac{kT}{S}} \sqrt{\ln t/\tau_0} \quad (10)$$

and for the quadratic barrier with $H \ll H_0$

$$H_{\text{eff}}(t, T) = H + \frac{kT}{2SH_0} \ln t/\tau_0. \quad (11)$$

We now define S'_v as the coefficient standing at $f(t) = \ln t$ or $(\ln t)^{1/2}$ in Eqs (9), (10) and (11). Whence we get

$$S'_v = \frac{kT}{L} = \begin{cases} \frac{kT}{2VI_s} & \text{for barrier (5a)} \\ \frac{ckT}{VI_s} & \text{for barrier (5c)} \end{cases}$$

$$S'_v = \frac{kT}{2SH_0} = \begin{cases} \frac{kT}{VI_s} & \text{for barrier (5b), } H \ll H_0 \\ \frac{4\pi kT}{3H_m V} & \text{for barrier (5d), } H \ll H_0 \end{cases}$$

$$S'_v = \sqrt{\frac{kT}{S}} = \begin{cases} \frac{2}{I_s} \cdot \sqrt{\frac{K_u kT}{V}} & \text{for barrier (5b)} \\ \sqrt{\frac{8\pi kT}{3V}} & \text{for barrier (5d).} \end{cases} \quad (12)$$

The next section deals with the description of the relaxation phenomenon by means of the concept of the effective value of magnetic field just defined.

3. Description of the relaxation phenomenon on terms of H_{eff} and Preisach's diagram

As in the considerations of Preisach [16] and Néel [15], it is assumed that only the irreversible component of magnetization (I_{irr}) exists in the sample and that it is described by a Preisach diagram. In the diagram the vertical axis now should carry, instead of the usual interaction fields (H_i) or external fields (H), the effective value (H_{eff}) of their resultant

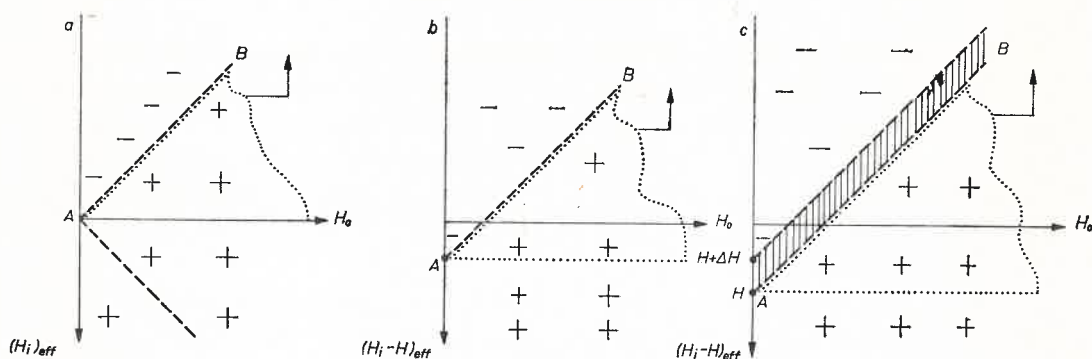


Fig. 1. Illustration of magnetic relaxation on Preisach diagram. Vertical axis carries effective values (eff) of resultant interaction field (H_i) and external field (H) for time $t = \tau_0$. Horizontal axis carries values of coercive force of the various microregions (H_0), thermal excitation being neglected. The "+" sign pertains to magnetic moments parallel to direction of initially applied saturating field. a) Distribution of microregion magnetization in sample after saturating field stops acting; b) distribution of microregion magnetization after change of field from saturation to a value $H + \Delta H$ (inverse); c) distribution of microregion magnetization after field ΔH ($\Delta H > 0$) is removed

(according to formula (9), (10) or (11), with time t counted from the instant a jump-wise change of field H appears). The coercive force of the microregions (H_0) is on the horizontal axis.

Figure 1 presents the magnetization distribution for the various phases of a relaxation measurement by the Street-Woolley method [18, 19]. For the sake of simplification, the diagrams are plotted for $H_{\text{eff}} = (H_i - H)_{\text{eff}} = H_i - H$, that is, for $t = \tau_0$. For actual times of magnetic field switch-overs ($t \gg \tau_0$) the diagrams are similar, the only difference being that the dot-shadowed regions are shifted up over the line AB .

In the regions bounded in Fig. 1 by dots the resultant magnetic field is negative and directed oppositely to the magnetic moments of the microregions. With increasing t the effective value of the field in these regions rises according to one of the formula (9), (10) or (11). This causes these regions to become shifted in entity, without any change in shape and internal field distribution, from the horizontal dotted line upwards by $S'_v \Delta f(t)$, where $f(t)$ is the time function of formula (9), (10) or (11), and S'_v is the coefficient given by one of formulae (12).

The line AB in Fig. 1 is that at which $H_{\text{eff}} = (H_i - H)_{\text{eff}} = H_0$, i. e. $t = \tau$. Hence, after reaching this line microregions have their magnetization reversed. This brings about a drop in magnetization with time, hence, magnetic relaxation.

The change in magnetization of the sample should be equal to $2S'_v \Delta f(t) \times A$, where A is the magnetization density along the boundary line AB . Here, magnetization density is understood to mean the change in magnetization effected by an infinitely small change in the field within a fixed time t , or

$$A = \frac{1}{2} \left(\frac{\partial I}{\partial H_{\text{eff}}} \right)_{H_{\text{eff}}=H_0} = \frac{1}{2} \left(\frac{\partial I}{\partial H} \right). \quad (13)$$

The factor $1/2$ appearing in Eq. (13) stems from the change in sign of magnetic moments from $+$ to $-$ when the line AB is crossed. In the case when only the irreversible magnetization component exists we have $\partial I / \partial H = \partial I_{\text{irr}} / \partial H = \chi_{\text{irr}}$.

To illustrate formula (13), the microregions lying between $H + \Delta H$ and H are cross-hatched in Fig. 1c. Their magnetization is $B = \Delta I_{\text{irr}} / 2$, and their magnetization density

$$A = \frac{1}{2} \frac{\Delta I_{\text{irr}}}{\Delta H} = \frac{B}{\Delta H} \xrightarrow{\Delta H \rightarrow 0} \frac{1}{2} \frac{\partial I_{\text{irr}}}{\partial H}.$$

Therefore, the change in the sample's magnetization is given by the formula

$$\Delta I = S'_v \Delta f(t) \times \chi_{\text{irr}} \quad (14a)$$

or

$$S_H = \frac{\Delta I}{\Delta f(t)} = S'_v \chi_{\text{irr}}. \quad (14b)$$

For the linear and quadratic barriers with $H \ll H_0$, $f(t) = \ln t$ and the relation (14b) is identical with the experimental relation of Street and Wolley. S'_v given by one of formulae (12) is the relaxation constant $-S_v$.

For the quadratic barrier at high H , we have $f(t) = (\ln t)^{1/2}$; this type of relaxation has also been observed experimentally [3].

4. Experimental consequences of magnetic field effective value concept

In this section the notation is introduced: I_{rev} , I_{irr} and I for reversible, irreversible and total magnetization, and χ_{rev} , χ_{irr} and χ for reversible, irreversible and total susceptibility:

a) $I_{\text{rev}} = 0$

This is the case already encountered in Section 3. Now we shall consider an example

of a linear barrier and a quadratic barrier for small H which reduces to the former. Assuming that the material constant of formula (6a) is $L = L(T)$, relations (7) give

$$\left(\frac{\partial H_c}{\partial T}\right)_{t'} = - \frac{-kL - kT(\partial L/\partial T)}{L^2} \ln t'/\tau_0 \quad (15)$$

and

$$\left(\frac{\partial H_c}{\partial \ln t}\right)_{T_0} = - \frac{kT_0}{L(T_0)}. \quad (16)$$

Whence

$$A \stackrel{\text{def}}{=} \left(\frac{\partial H_c}{\partial T}\right)_{t'} / \left(\frac{\partial H_c}{\partial \ln t}\right)_{T_0} = \left[\frac{1}{T_0} - \frac{1}{L(T_0)} \left(\frac{\partial L}{\partial T}\right)_{T_0} \right] \ln t'/\tau_0. \quad (17a)$$

If in the range of measurement temperatures the dependence of L on T can be neglected, then formula (17a) becomes simplified to the form

$$\left(\frac{\partial H_c}{\partial T}\right)_{t'} / \left(\frac{\partial H_c}{\partial \ln t}\right)_{T_0} = \frac{\ln t'/\tau_0}{T_0}. \quad (18a)$$

Since the quantities appearing in the left-hand side of Eq. (18a) can be determined experimentally, it can be used for finding τ_0 at a given temperature and field $H \approx H_c$. Formula (17a), on the other hand, allows τ_0 to be determined if the function $L(T)$ is known.

An additional assumption is that $\tau_0 \neq \tau_0(H, T)$. The dependence of τ_0 on H as postulated by Brown [4] and Aharoni [1] is weak in comparison with the exponential dependence of τ on H and may therefore be disregarded. If the dependence of τ_0 upon T must be taken into account, then we get the following relations:

$$A = \left[\frac{1}{T_0} - \frac{1}{L(T_0)} \left(\frac{\partial L}{\partial T}\right)_{T_0} \right] \ln t'/\tau_0 - \frac{1}{\tau_0} \frac{\partial \tau_0}{\partial T} \quad (17b)$$

and

$$A = \frac{\ln t'/\tau_0}{T_0} - \frac{1}{\tau_0} \frac{\partial \tau_0}{\partial T}. \quad (18b)$$

According to Aharoni [1], $\tau_0 \approx CT^{1/2}$, while Stacey [22] obtained from general considerations that $\tau_0 \approx CT^{-1}$. Assuming $\tau_0 = CT^n$ we get

$$-\frac{1}{\tau_0} \frac{\partial \tau_0}{\partial T} = -\frac{n}{T_0}. \quad (18c)$$

Hence, when it is assumed that $\ln t'/\tau_0 \approx 25$ (see [14,4]), the ratio of the first and second members in formula (18b) equals $-25/n$, which gives a value of 50 for the $\tau_0(T)$ dependence of Aharoni and -25 for Stacey's dependence. It is obvious that if we should treat these two dependences as the first approximation of τ_0 , then the corrective terms on the right-hand side of Eqs (17b) and (18b) may be neglected.

In stricter considerations we must further take account of changes in H_0 with temper-

ature, and the left-hand side of Eqs (17a, b) and (18a, b) takes the form

$$A \stackrel{\text{def}}{=} \frac{\left(\frac{\partial H_c^{\text{exp}}}{\partial T} - \frac{\partial H_0}{\partial T} \right)_{T'}}{\left(\frac{\partial H_c}{\partial \ln t} \right)_{T_0}}. \quad (19)$$

For the relaxation of the irreversible magnetization component the Preisach diagram or straightforwardly the mathematical equalities can be found to give the relations

$$\begin{aligned} \left(\frac{\partial I_{\text{irr}}}{\partial T} \right)_{T'} &= \left(\frac{\partial I_{\text{irr}}}{\partial H_{\text{eff}}} \right) \times \left(\frac{\partial H_{\text{eff}}}{\partial T} \right)_{T'} \\ \left(\frac{\partial I_{\text{irr}}}{\partial \ln t} \right)_{T_0} &= \left(\frac{\partial I_{\text{irr}}}{\partial H_{\text{eff}}} \right) \times \left(\frac{\partial H_{\text{eff}}}{\partial \ln t} \right)_{T_0}. \end{aligned} \quad (20)$$

In Eqs (20) and henceforth we drop the subscript H which indicates the value of constant field in which magnetization is measured.

On the basis of formulae (20) and (9) for $H_{\text{eff}}(t, T)$ it is possible to find in like manner as before the expression

$$B = \left(\frac{\partial I_{\text{irr}}}{\partial T} \right)_{T'} / \left(\frac{\partial I_{\text{irr}}}{\partial \ln t} \right)_{T_0} = \left[\frac{1}{T_0} - \frac{1}{L(T_0)} \left(\frac{dL}{dT} \right)_{T_0} \right] \ln t / \tau_0 - \frac{n}{T_0}. \quad (21)$$

This formula does not take account of the dependence of H_0 on T nor of τ_0 on H . An experimentally determined value of $B(H, T)$ permits τ_0 to be calculated for various temperatures and fields. Also, $B(H) \rightarrow A$ when $H \rightarrow H_c$.

b) $I_{\text{rev}} \neq 0$

What follows in this subsection is pertinent to a majority of magnetic substances. We now have $I = I_{\text{rev}} + I_{\text{irr}}$.

As the reversible magnetization component is in instantaneous equilibrium with the field ($\partial I_{\text{rev}} / \partial \ln t = 0$), hence,

$$\frac{\partial I}{\partial \ln t} = \frac{\partial I_{\text{irr}}}{\partial \ln t} = \frac{\partial I_{\text{irr}}}{\partial H_{\text{eff}}} \times \frac{\partial H_{\text{eff}}}{\partial \ln t} = \chi_{\text{irr}} \times S_V. \quad (22a)$$

It is evident that the Street-Woolley experimental relation remains valid.

For temperature variations of magnetization we can write

$$\frac{\partial I}{\partial T} = \frac{\partial I_{\text{irr}}}{\partial H_{\text{eff}}} \times \frac{\partial H_{\text{eff}}}{\partial T} + \chi_{\text{irr}} \frac{\partial H_0}{\partial T} + \frac{\partial I_{\text{rev}}}{\partial T}. \quad (22b)$$

It follows from Eqs (22a, b) that

$$B = \frac{\left[\left(\frac{\partial I}{\partial T} - \frac{\partial I_{\text{rev}}}{\partial T} \right) - \chi_{\text{irr}} \frac{\partial H_0}{\partial T} \right]_{T'}}{\left(\frac{\partial I}{\partial \ln t} \right)_{T_0}} = \left[\frac{1}{T_0} - \frac{1}{L(T_0)} \left(\frac{dL}{dT} \right)_{T_0} \right] \ln t' / \tau_0 - \frac{n}{T_0}. \quad (23)$$

It is rather difficult to experimentally determine $\partial I_{\text{rev}}/\partial T$. The value of dH_0/dT can be estimated theoretically or, as in the study of Craik and Wood [6] for thin magnetic films, be determined experimentally.

Near $I \approx 0$, that is, for $H \approx H_c$, it is easily seen that

$$\frac{\partial H_c}{\partial \ln t} = \frac{\partial I}{\partial \ln t} / \chi, \quad \frac{\partial H_c}{\partial T} = \frac{\partial I}{\partial T} / \chi. \quad (24)$$

From formulae (23) and (24) we get

$$B(H_c) \stackrel{df}{=} A = \frac{\left[\left(\frac{\partial H_c}{\partial T} - \frac{1}{\chi} \frac{\partial I_{\text{rev}}}{\partial T} \right) - \frac{\chi_{\text{irr}}}{\chi} \frac{\partial H_0}{\partial T} \right]_{t'}}{\left(\frac{\partial H_c}{\partial \ln t} \right)_{T_0}} =$$

$$= \left[\frac{1}{T_0} - \frac{1}{L(T_0)} \left(\frac{dL}{dT} \right)_{T_0} \right] \ln t' / \tau_0 - \frac{n}{T_0}. \quad (25)$$

Formula (25) for $I_{\text{rev}} = 0$ converts into (17b) with an additional member accounting for the $H_0(T)$ dependence. Similarly, formula (23) converts into (21).

5. Discussion of the various forms of energy barriers

a) For the reversal of magnetization of an accumulation of magnetic particles having a chaotic distribution of easy axes we find from Eqs (5c), (6a) and (12) for $S'_v = S_v$ the relations:

$$L = \frac{VI_s}{c}, \quad H_0 = c \frac{K_u}{I_s}, \quad (26)$$

and

$$S_v = \frac{kT}{L} = \frac{ckT}{VI_s}. \quad (27)$$

Formula (27) enables the volume of the relaxing region to be calculated for $T = T_0$. The proportionality of S_v to T contained in it is satisfied only in the case when V for various fields H is the same. Such is the case when we describe the sample by means of a Preisach diagram, for then we assume an identical value of V for all microregions of different H_0 (this will be discussed further in Sec. 6).

To simplify Eqs (17b), (21) and (23), let us calculate the ratio of the two members in the brackets of the right-hand side of these formulae. We get

$$\frac{1}{T_0} / \frac{1}{L} \frac{dL}{dT} = \frac{I_s(T_0)/T_0}{\frac{dI}{dT}}.$$

Should we limit ourselves to $T \ll T_c$, where $\left| \frac{dI_s}{dT} \right| \ll \frac{I_s(T_0)}{T_0}$, then the second term in the brackets of the formulae in mention may be neglected.

For temperature variations of H_0 we can write

$$\frac{dH_0}{dT} = \frac{cI_s \frac{dK_u}{dT} - cK_u \frac{dI_s}{dT}}{I_s^2}$$

It is thus seen that the relevant member on the left-hand side of Eq. (25) is negligible as had been the case in formulae (17b), (21) and (23), insofar as we neglect dK_u/dT . This, in turn, owing to the rather strong dependence of K_u on T , makes it necessary to limit the temperature changes (to the order of several tens of degrees) in the measurements.

Preliminary experimental results have been obtained for a Cu-1% Co single crystal [8]. The single crystal of this alloy, after being homogenized three hours at 1000°C, was slowly cooled to room temperature. During this cooling process fine ferromagnetic cobalt particles precipitated in the sample. The measurements, carried out on the apparatus described in Refs [7, 12], showed that $\Delta I \sim \Delta \ln t$ and $\Delta H_c \sim \Delta \ln t$. The value of S_v was not entirely stable, but diminished down to several tens of per cent as the inverse field rose to about 100 Oe, *i. e.* to H_c several times over. Measurements for finding τ_0 were performed for remanance relaxation. To determine τ_0 , use was made of the simplified version of Eq. (21), *viz.*, it was assumed that $dL/dT = 0$, $d\tau_0/dT \approx 0$ and $I_{rev} \approx 0$. Obviously, with such assumptions it was possible only to determine the order of magnitude of τ_0 . The results obtained for one sample are:

$$\begin{aligned} \tau_0 &= 5 \times 10^{-8} \text{ s for } 77 \text{ K,} \\ &8 \times 10^{-9} \text{ s for } 100 \text{ K,} \\ &1.1 \times 10^{-7} \text{ s for } 150 \text{ K,} \\ &7.4 \times 10^{-8} \text{ s for } 200 \text{ K,} \\ &2.2 \times 10^{-8} \text{ s for } 300 \text{ K.} \end{aligned}$$

The mean value of these results is $\tau_0 = 4.4 \times 10^{-8}$ s. New results will be published after the cause of the straggling is eliminated.

b) For magnetization reversal *via* domain wall movements it is possible to interpret within the framework of the theory presented here the work of Hellenthal [9] and Craik and Wood [6], getting results identical with those of these authors and Wohlfarth [21].

To do this for Hellenthal's results we rewrite Eq. (7) into the form

$$H_c(t, T) = H_0 - S_v \ln t / \tau_0$$

whence

$$\ln t = \left(\frac{H_0}{S_v} - \ln \tau_0^{-1} \right) - \frac{H_c}{S_v} \quad (28)$$

This formula is identical with the experimental relation of Hellenthal,

$$\ln t = 23.7 - \frac{7.6}{\text{Oe}} \cdot H_c \quad (29)$$

Accepting the energy barrier given by Eq. (5b) in the $H \ll H_0$ approximation we have from formula (12)

$$S_v = \frac{kT}{VI_s}, \quad H_0 = \frac{K_u}{I_s} \quad (30)$$

Comparing Eqs (28) and (29), and considering the relations (30), we get with the assumption $\tau_0 \approx 10^{-8}$ s the following values:

$$H_0 \cong 5.55 \text{ Oe}, \quad V = 6.5 \times 10^{-15} \text{ cm}^3 \quad (r = 540 \text{ \AA})$$

$$H_K \stackrel{\text{def}}{=} 2K_u/I_s = 2H_0 \cong 11.1 \text{ Oe}$$

hence, results which are in agreement with the studies of Hellenthal and Wohlfarth.

In order to apply the formal theory developed in Sec. 4 to the results of Craik and Wood [6], it must be assumed that $dH_0/dT = dH_k/dT$ (Fig. 7 of Ref. [6]). Disregarding the dependence of L and τ_0 on T and assuming $I_{\text{rev}} = 0$, it is possible to write on the basis of relations (17b) and (19):

$$\Delta = \frac{\left(\frac{\partial H_c^{\text{exp}}}{\partial T} - \frac{\partial H_k}{\partial T} \right)_{T'}}{\left(\frac{\partial H_c}{\partial \ln t} \right)_{T_0}} = \frac{\ln t'/\tau_0}{T_0} \quad (31)$$

Making use of the data of Figs 4, 6 and 7 of the work by Craik and Wood, we get such values as:

$$\log \tau_0 = -9.5 \quad (\text{for } t' = 10 \text{ s and } T_0 = 273 \text{ K}),$$

$$\log \tau_0 = -9.3 \quad (\text{for } t' = 1 \text{ s and } T_0 = 238 \text{ K}),$$

$$\log \tau_0 = -7.6 \quad (\text{for } t' = 1 \text{ s and } T_0 = 273 \text{ K}),$$

which yield an average of $\log \tau_0 = -8.8$, or $\tau_0 = 1.6 \times 10^{-9}$ s.

It should be mentioned that formula (31) and the other ones determining τ_0 are independent of the assumed mechanism of magnetization reversal, *i. e.* of the choice of one of the linear energy barriers given by Eqs (5).

6. Statistical models describing the magnetic relaxation phenomenon

In this paper the Preisach diagram formalism was used to describe the magnetic relaxation formalism. In this case we assume a distribution of the interaction fields of the microregions in the sample (H_i) and a distribution of the coercive forces of these microregions (H_0). But for the entire diagram, that is, for all microregions, we assume the same volume V .

There also exists an alternative description first given by Street and Woolley [19]. In it, it is assumed that there is an effective distribution of energy barriers in the direction of the applied field $E(H)$. For fine-particle type substances this may be, for instance, the distribution of the effective value of the product $K_u V$ along the direction of the applied field. On the other hand, the internal interaction field is disregarded.

In this case the scheme of Fig. 2 and the formula

$$H_{\text{eff}} = H_0 + S_v \ln t/\tau_0 \quad (32)$$

should be used for describing the relaxation. The energy barrier (e. g. $K_u V - \frac{1}{c} V I_s H$ for fine-particle material) is laid off on the horizontal axis in Fig. 2. The application of an inverse field H causes changes of sign in some of the microregions, the boundary line shifting with time as given by formula (32), thereby giving rise to relaxation according to the formula

$$\Delta I_{\text{irr}} = \chi_{\text{irr}} S_v \Delta \ln t.$$

With an increase in field, and $\ln t$ also, S_v shifts towards regions of higher $E(H)$. Insofar as the $E(H)$ distribution is correlated with the distribution of V , for the higher inverse fields and longer relaxation times there will presumably appear higher V . Therefore, S_v , which is proportional to $1/V$, will diminish monotonically with growing H and $\ln t$.

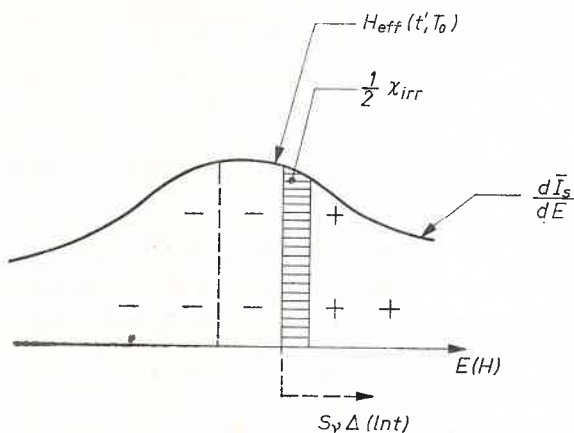


Fig. 2. Distribution of magnetization relative to energy barrier of microregions in field H applied inversely to saturating field. The “+” and “-” signs correspond to microregions of magnetic moments aligned with an against the saturating field applied earlier

It may be intuitively ascertained that strong magnetic interaction will cause the simultaneous occurrence of entire groups of jumps of aggregate volumes not very different from one another (see Stierstadt [17]). Then the sample is described by the Preisach diagram, in which all microregions are assumed to have identical volumes. For example, this will describe the relaxation in materials of the Alnico type (as opposed to the model adopted by Street and Woolley, Fig. 2).

On the other hand, the acceptance of a volume distribution and simultaneous neglect of interaction fields (hence, the model of Fig. 2) will apply to materials of the fine-particle type having a low percentage of ferromagnetic component (e. g., the Cu-1% Co solid solution). Then, S_v will additionally be dependent on H and $\ln t$, viz., $S_v = S_v(V(H, \ln t))$.

7. Conclusions

The concept of the effective value of magnetic field (see Eqs (9) and (32)) introduced here on the basis of the fundamental formula (2) replaces the field of thermal fluctuations of Néel in the description of relaxation. The concept of the effective value of field together with various energy barriers $E(H)$ (Eqs (5)) and the two different models statistically describing the sample with strong (Fig. 1) and weak (Fig. 2) interaction allow many of the seemingly different relaxation phenomena to be explained. For example, it has been proved that the temperature dependence of the relaxation constant is the outcome of the dependence of energy barrier on magnetic field in the given magnetic material, similarly as the time dependence of magnetization relaxation. The constancy of $S_v(H)$ is closely linked with the assumed model of strong interaction (i. e. the Preisach diagram). If interaction is weak, then the distribution of V becomes significant and, hence, $S_v = S_v(V(H, \ln t))$ where V is the volume for which condition (8) is momentarily satisfied.

Moreover, the dependence of relaxation on T , H and $\ln t$ may be further modified when these parameters are so chosen that we go beyond or reach the boundary of the region of the energy barrier distribution (e. g. large inverse fields). A discussion of this effect will not be given in the foregoing, however.

The formula derived in this study allows the constant τ_0 to be determined for various substances at various states (T , H). The values of τ_0 obtained thus are of the same order of magnitude as those of theoretical postulates and literature data. The conformity of the experimentally determined order of magnitude of τ_0 for rotations and domain wall movements, and the duality of the interpretation of magnetization reversal processes leading to identical results, are striking. This points to the same mechanism of thermal excitation of magnetization reversal processes in both cases. Its quantum mechanical interpretation based on the activation of spin waves should be essentially different than the classical analysis of the rotations of the magnetic moment vector made by Néel [14], Brown [4], and Aharoni [1].

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