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Magnetic After-Effect. II*

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Synopsis

A theory of the magnetic after-effect was developed on the assumption that the after-effect is an exhaustion phenomenon, and discussed in terms of the retardation of irreversible magnetic wall displacement. The phenomenological theory reported in the previous paper was compared with the present one, and the intimate relation between them was suggested.

I. Introduction

In general, the displacement velocity \( v \) of a magnetic boundary in the field \( H \) is given by

\[ v = a(H - H_0), \]

where \( H_0 \) is the strength of the critical field. This expression signifies that the magnetic boundary should move very slowly in the field slightly larger than \( H_0 \). Consequently, the retarded change in magnetization should be observed in the course of the magnetic after-effect. The irreversible magnetization process in the course of the after-effect was observed by the present author\(^{(1)}\), and it was concluded that the retardation of the boundary displacement might be the main origin of the after-effect in the region of irreversible magnetization. The characteristics of magnetic after-effect of this sort were explained by the theory\(^{(2)}\) based on this model. \( H_0 \) is the smallest strength of the external field necessary to displace the magnetic boundary and, consequently, all magnetic boundaries stay at the positions where \( H_0 \) is larger than \( H \). When, however, \( H_0 \) is decreased for some reason and becomes smaller than \( H \) at any place where the magnetic boundary has been anchored, this boundary comes to move under the action of the external field \( H \). In this respect, \( H_0 \) seems to be a frictional force acting on the magnetic boundary during its displacement. By various investigations, \( H_0 \) has been found to be related with the existence of internal stress. One of the evidences for this assumption is that Barkhausen effect is always observable when a ferromagnetic substance is stretched by an increasing force: An external force changes the distribution and the amount of internal stresses and, consequently, the value of \( H_0 \). When \( H_0 \) decreases, the magnetic boundary moves irreversibly, and the change in magnetization due to this boundary displacement may be observed in Barkhausen phenomena. On the other hand, if the fluctuation in internal stress has something

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to do with the thermal origin instead of with the effect of external stress, the relaxed displacement of the magnetic boundaries caused by the similar mechanism will take place in the course of the magnetic after-effect. In the present research, a theory of the magnetic after-effect was developed on the basis of the exhaustion model, by taking account of this thermal fluctuation of critical field $H_0$.

II. Theory of magnetic after-effect

In all cases in which formal theories of the magnetic after-effect are developed, models are used merely for convenience. In the present case, the specimen is regarded as being composed of a large number of elements having the following properties: (1) Each element is characterized by a certain activation energy and can be activated by thermal fluctuations; (2) when an element is thermally activated, it undergoes a jump, and after the occurrence of a jump in an element the activation energy becomes infinite; (3) the jumps in the elements are independent of one another, i.e., the activation energy is unaffected by jumps in other elements; (4) the activation energy is assumed to be given by $qJ_s(H_0 - H)$ in the field $H$, where $q$ is the volume in which thermal fluctuation takes place and $J_s$ the saturation value of magnetization.

Now, let $n(H_0 - H, t) d(H_0 - H)$ be the number of elements with the activation energies in the range $(H_0 - H) < (H_0 - H) + \Delta H$ at the time $t$ after the start of the after-effect. The chance at which an element in the state $(H_0 - H)$ will jump during the increment of time $dt$ is given by

$$ f(H_0 - H) dt = \nu dt \exp \left\{ -\frac{U(H_0 - H)}{kT} \right\} , \quad (2) $$

where $\nu$ is the frequency of the vibration of an atom and $U$ the activation energy. When each jump is supposed to contribute a fractional increase $\Delta J$ in magnetization to the overall creeping of magnetization, the rate of change in magnetization will be

$$ \frac{dJ}{dt} = \Delta J \int n(H_0 - H, t) f(H_0 - H) \, d(H_0 - H) . \quad (3) $$

The number of available elements remaining in each range of activation energy decreases at the rate

$$ \frac{\partial}{\partial t} n(H_0 - H, t) = -n(H_0 - H, t) f(H_0 - H) , \quad (4) $$

By integration, it will become

$$ n(H_0 - H, t) = n(H_0 - H, 0) \exp \left\{ -f(H_0 - H) t \right\} , \quad (5) $$

where $n(H_0 - H, 0)$ is the distribution of elements at the start of the after-effect. By Eq. (2),

$$ -\frac{kT}{qJ_s} df(H_0 - H) = f(H_0 - H) \, d(H_0 - H) . \quad (6) $$
The rate of change in magnetization is given by

\[ \frac{dJ}{dt} = -\frac{\Delta J n k T}{q J_s} \int_{f(0)}^{f(H_0 - H_m)} \exp \left\{ -f(H_0 - H) t \right\} df(H_0 - H) \]

\[ = \frac{\Delta J n k T}{q J_s t} \left( \exp \left( -\frac{t}{t_0} \right) - \exp \left( -\frac{t}{t_m} \right) \right), \quad t_0 < t < t_m, \quad (7) \]

where

\[ t_0^{-1} = f(0) = \nu, \quad t_m^{-1} = f(H_0 - H_m) = \nu \exp \{ -q J_s (H_0 - H_m)/kT \} \]

When \( t_0 \ll t \), the factor in the bracket in Eq. (7) is essentially unity and, accordingly,

\[ \frac{dJ}{dt} = \frac{\Delta J n k T}{q J_s} \cdot \frac{1}{t}. \quad (8) \]

Then, the time law of the after-effect is given by

\[ J = \frac{\Delta J n k T}{q J_s} \ln t \bigg|_{t=1/\nu}^t \]

\[ = \frac{\Delta J n k T}{q J_s} \ln \nu t. \quad (9) \]

As regards the time law of the after-effect, Eq. (9) is equivalent to Eq. (6) given in the previous paper\(^3\), which was obtained as a fundamental expression of the magnetic after-effect.

### III. Discussion

Eq. (9) is a typical expression of the exhaustion theory which signifies that the after-effect is proportional to the logarithm of time. Another investigation on the logarithmic time law of after-effect was already described in the previous paper\(^3\): that is, by taking into account the change in the effective field due to the change in magnetization, a theoretical equation was deduced, which could explain the characteristics of the magnetic after-effect observed. Moreover, it was formally concluded that the activation energy necessary to displace a magnetic boundary increased with the logarithm of time in the course of the after-effect. On the other hand, Néel\(^4\) studied the magnetic after-effect on the assumption that the disturbance of internal magnetic field due to thermal fluctuation is a main origin of the magnetic after-effect, and concluded that the disturbance of the internal field could be approximately substituted for the internal field which increased with the logarithm of time in the course of the after-effect. As remarked previously, however, these two theories lead to the same conclusion that the effective field increases in proportion to the logarithm of time.

As the strength of the critical field \( H_0 \) depends on the amount and the distribution of internal stresses, \( H_0 \) changes from point to point in a ferromagnetic

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substance. Now, when the magnetizing field is suddenly changed, most of the unstable boundaries \((H>H_0)\) move instantaneously toward new equilibrium positions. If, however, the critical field \(H_0\) is assumed to be a value which varies close to the external field \(H\) in some region of the ferromagnetic subsuance where the boundary happens to lie, they should move at a very small velocity, taking a certain amount of time to pass through the region. If \(H_0\) at the boundary diminishes after passing this region, the boundary will thenceforth move rapidly, and Barkhausen jumps may occur on the occasion. Thus, the retarded Barkhausen jumps will become observable in the course of the magnetic after-effect even after the change of magnetization has almost been completed. An experimental evidence of the retarded Barkhausen jumps in the course of the after-effect is shown in Fig. 1. In the figure, the total number of Barkhausen jumps in the interval ranging from 0.3 to 1.3 sec. after the change of external field is plotted against various final stages of magnetization in the descending branch of hysteresis curve. It will be seen that the maximum occurrence of Barkhausen jumps is near the steepest part of the hysteresis curve where the process of discontinuous magnetization takes place. The previous discussion on the magnetic after-effect was based on this experimental evidence, but it must be remarked now that as the displacement velocity of a magnetic boundary is determined by the value of \((H-H_0)\), the time of retardation should depend on the value of \(H_0\) and, accordingly, the boundary can be characterized by its proper rest time before the jump instead of by \(H_0\), provided that the Barkhausen effect is the experimental evidence of relaxation phenomena in the after-effect. In the present formal theory, the element has its proper activation energy which is given by \(q_jH_0\), but there is, in general, one to one correspondence between activation energy and relaxation time and, accordingly, the element can be characterized by its proper relaxation time instead of by activation energy, or, \(H_0\). That is, the element symbolized by \(H_0\) is characterized by the proper rest time in the former case, while, by the proper relaxation time in the latter. Then, an intimate relation between the phenomenological theory and the present formal one may be suggested by the retardation of Barkhausen jumps. Moreover, it should be noticed that if, activation energy is expressed by \(kT\log\nu t\),
the relaxation time becomes $t$ by Eq. (2), that is, the element of which activation energy is equal to $kT\log \nu t_1$ is designated by the relaxation time $t_1$. (Supposing $t_1$ to be 1 sec., the activation energy is estimated to be 0.6 eV, the plausible magnitude in order.)

After all, the after-effect in the region of irreversible magnetization can be explained from three kinds of assumption: (1) The specimen is regarded as being composed of a large number of elements having various kinds of rest time. (Retardation of Barkhausen jumps.) (2) Every element has an appropriate activation energy. (Exhaustion theory.) (3) The activation energy increases in proportion to the logarithm of time. (Formal theory.) But, the above theories do not refer to the activation process, i.e. the mechanism of retardation is not yet made clear in detail. It has already been pointed out that the activation energies are about 0.2 eV and 0.6 eV respectively at $-196^\circ$ and at room temperature in the cases of Ni$_3$Mn and Fe. According to various experiments on the recovery phenomena, the activation energy are classified into three groups, namely, 0.2, 0.6 and 1 eV respectively at $-196^\circ$, at room temperature and at temperatures above 200$, and the present estimations fairly well agree with these values. Hence, the magnetic after-effect in the region of irreversible magnetization process may be studied on the base of the activation process directly related with the behaviour of imperfections, or, the diffusion phenomena in metal crystals. The local variation of internal stress which is assumed to be the main origin of the critical field can arise from the misfit of atom due to impurities, lattice imperfections and dislocations, etc. It seems to be very difficult to solve this problem theoretically, but the following argument on the displacement of a magnetic boundary, though speculative, will be interesting. For simplicity, let us assume that a small portion $s$ of a magnetic boundary moves over a certain distance $l$ passing through the obstacle and that the activation energy necessary for its displacement is given by $slH_0$. Though $s$ and $l$ cannot be estimated accurately, the following fact will be of some use as a good reference in the estimation. By the observation of Barkhausen effect, the volume and the distance in which a magnetic boundary moves under the field was estimated from the change in magnetization at single Barkhausen jump to be $10^{-8}$cm$^3$ and $10^{-2}$cm in order of magnitude. Hence, the sectional area of a magnetic domain boundary $s$ may be $10^{-7}$cm$^2$. Thus, when $q$, equal to $sl$, is $10^{-15}$cm$^3$, the value estimated in the previous paper, $l$ will become $10^{-4}$cm in order of magnitude. If a magnetic boundary can be set free from the anchoring and moves some atomic distances from the initial position, the anchoring should be caused by the force acting in small range, and in this respect, the localized stress field around lattice imperfections can be seen to be the main origin of the critical field and, consequently, some kind of diffusion process of lattice imperfections should play an important role in the mechanism of the magnetic after-effect. At present, however, the role of lattice imperfections in the

process of magnetization is speculative.

Summary

(1) The magnetic after-effect in the region of irreversible magnetization was explained on the exhaustion theory and the result was the same as that of the formal theory reported in the previous paper, in which it was assumed that the activation energy increased in proportion to the logarithm of time.

(2) The origin of relaxation was discussed from the viewpoint that the origin of magnetic after-effect was the retardation of displacement of magnetic boundaries and was suggested that the activation process of lattice imperfections might be the main origin of the after-effect.

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