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# After-Effect of Magnetostriction in Nickel*

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**Synopsis**

Magnetostrictive after-effect of nickel was observed, which appeared immediately after the completion of the change in applied magnetic field. Transient change in magnetostrictive deformation continues over several minutes and amounts to about 10 per cent of the saturation value of magnetostriction of nickel. The decay curve of this after-effect is fitted to the expression, $\varepsilon = C \log (t/t_0 + 1)$, where $\varepsilon$ is the amount of strain at time $t$ in the course of the after-effect.

## I. Introduction

When magnetic field applied to a ferromagnetic material suddenly changes, its magnetization instantly approaches a final equilibrium value, but a transient change in magnetization[1] takes place even after the change in magnetic field was complete. This phenomenon is called 'magnetic after-effect'. Magnetostriction is a deformation of the specimen that takes place simultaneously with the change in magnetization, and therefore, the transient change in magnetostriction should be observed in the course of magnetic after-effect. But this transient phenomenon has not yet been studied in detail. In order to measure the magnetostrictive deformation precisely as possible, one must care to avoid experimental errors due to fluctuation of temperature of the specimen, because the magnitude of magnetostriction is of the same order as the value of coefficient of thermal expansion or less. But, if one can master some difficulties of keeping the temperature of specimen constant, it is quite possible to measure the magnetostrictive deformation by using recent technique of strain measurement. In the present study, to obtain some informations of this transient phenomenon, the magnetostrictive after-effect in a nickel rod was observed by using a strain gauge of electric resistance type.

## II. Experimental procedure and results

The apparatus used is schematically shown in Fig. 1. A nickel rod, 29 cm in length and 4.5 mm in diameter, annealed at 800° C for 3 hr. in vacuum, is set inside a water jacket which is inserted in a magnetizing solenoid. One end of the specimen is fastened by a grip and the other end is connected to a rod of an unbounded type strain gauge. To avoid fluctuation of temperature due to inflow of air, both sides of the jacket are covered, but a thin rod of the strain gauge passes

* The 1144th report of the Research Institute for Iron, Steel and Other Metals.

(1) S. Maeda, J. Phys. Soc. Jap., **6** (1951), 494. T. Huzimura, J. Phys. Soc. Jap., **5** (1950), 2.

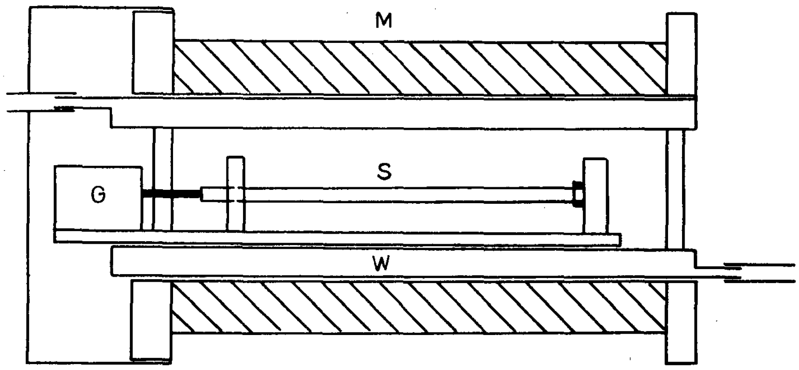


Fig. 1. Schematic representation of the apparatus of measuring magnetostrictive after-effect.
S: specimen. M: magnetizing solenoid.
W: water jacket. G: unbounded strain gauge.
Water circulates through the water jacket at a constant rate so as to keep the temperature of specimen constant.

through a small hole of the cover. As the strain sensibility of the gauge was about $10^{-6}$ cm, the change in length could be measured up to $3.5 \times 10^{-8}$ cm per unit length of the specimen. When the external magnetic field is absent, the change in length of the specimen is merely $3 \times 10^{-8}$ cm per unit length for 10 min. Accordingly, it is easy to check the experimental error due to the thermal expansion of specimen during the measurement of the after-effect.

After the specimen was magnetized up to near the saturation by applying magnetic field of 200 Oe for 2 min, the intensity of magnetization of the specimen

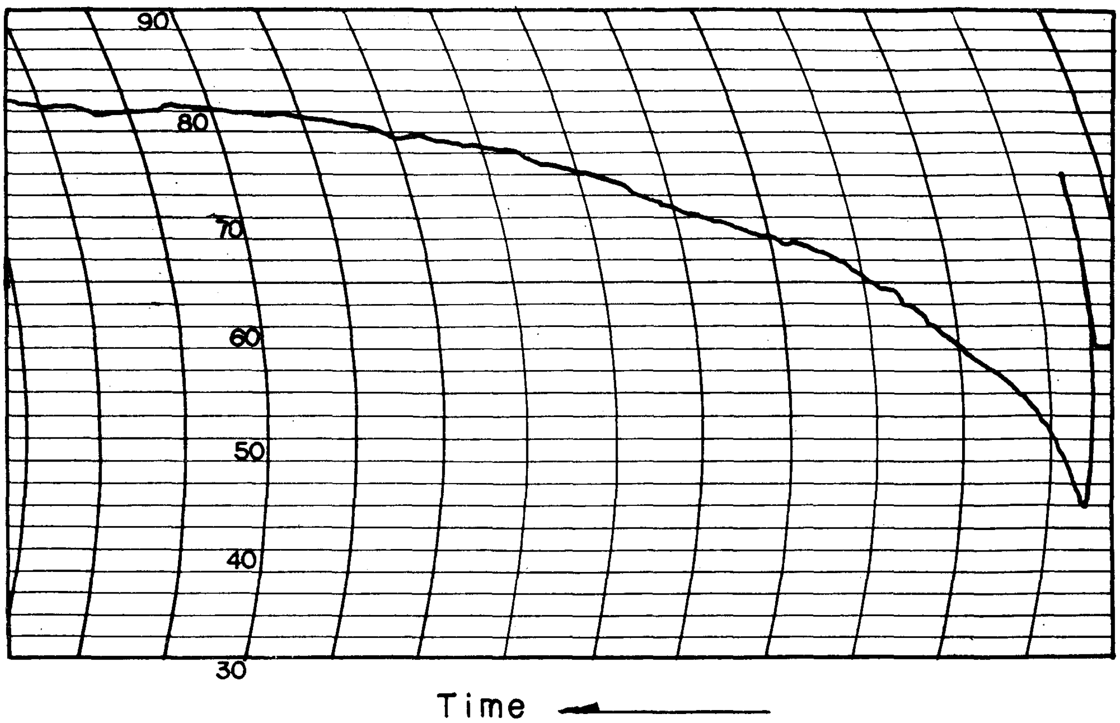


Fig. 2. A typical curve of magnetostrictive after-effect.

was reduced by changing magnetic field strength in the solenoid. Immediately after this moment, not only instantaneous, but also transitional changes in length of the specimen were recorded continuously on the chart paper of the strain

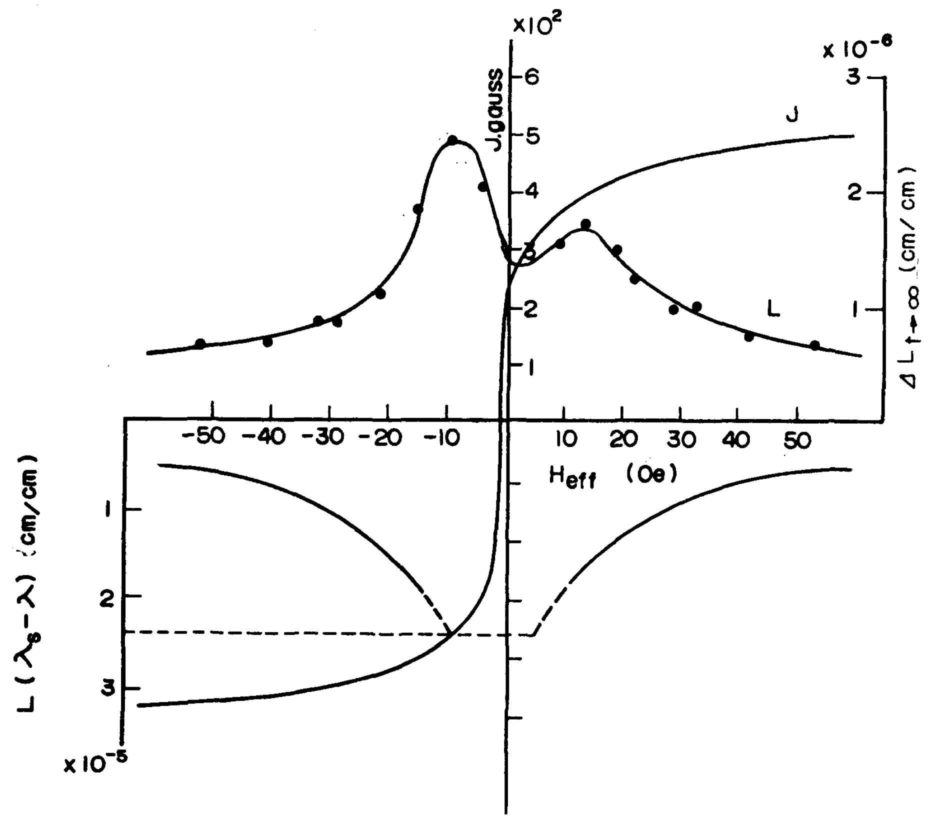


Fig. 3 Magnetic hysteresis curve of the specimen, the curve of $l$ versus $H_{eff}$ and the curve of $(\lambda_s-\lambda)$: versus $H_{eff}$.
$\lambda$: apparent magnetostriction. $\lambda_s$: saturation value of apparent magnetostriction.

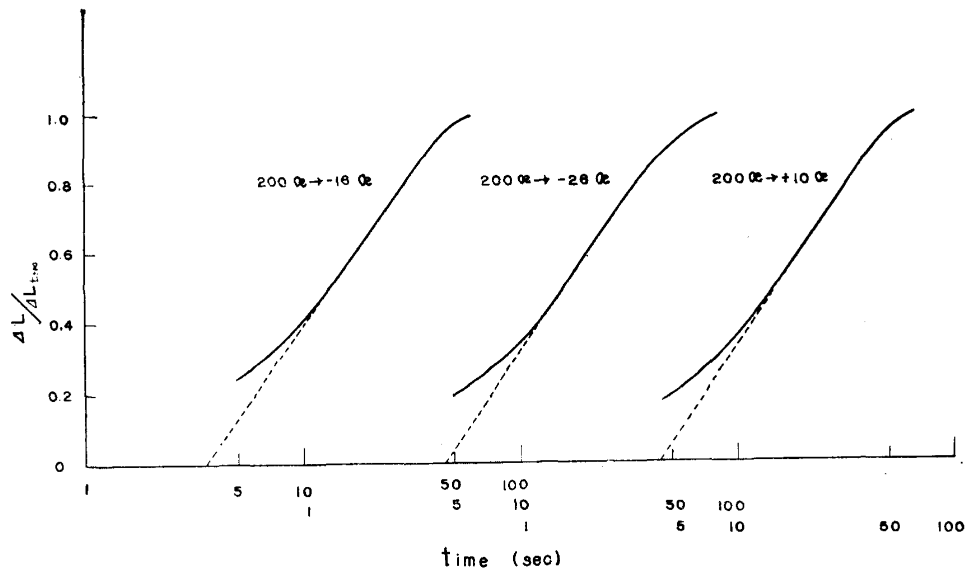


Fig. 4. The curves of $\Delta l/l_{t\to\infty}$ plotted against log $t$ for several cases.

meter. One of these records is shown in Fig. 2. As seen in the figure, most part of this transition phenomenon decays within several minutes and then a stationary creep seems to follow. In Fig. 3, the amounts of both instantaneous and transitional changes in the length of specimen, $l$ and $\Delta l$, respectively, are plotted against the strength of the effective magnetic field. $\Delta l$ amounts up to $2.5\times10^{-6}$ cm per unit length of the specimen, which is about 10 per cent of the saturation value of magnetostriction of nickel. Magnetic hysteresis curve is shown in the same figure. It will be seen that the transitional change predominates at the bend portion of the hysteresis curve and diminishes at the steep portion of the curve, and that except this range, $\Delta l_{t\to\infty}$ is approximately in proportion to $l$. In Fig. 4, $\Delta l/\Delta l_{t\to\infty}$ is plotted aginst $t$ in logarithmic scale for several cases. It will be seen that the change in $\Delta l/\Delta l_{t\to\infty}$ with log $t$ does not depend on the amount of magnetization of the specimen and that $\Delta l/\Delta l_{t\to\infty}$ can be expressed by C log $(t+\text{const.})$.

## III. Consideration and discussion

The effect of delayed displacement of magnetic domain walls was demonstrated by the experiment on 'Barkhausen effect' in the course of magnetic after-effect.(2) Barkhausen jump takes place most frequently at the steep part of descending branch of hysteresis curve, where displacement of 180°–wall is thought to be a predominant process of magnetization, whereas as shown in Fig. 2, the transient change in magnetostriction is observed predominantly at the bend portion of the hysteresis curve. Accordingly, it may be supposed that the delayed displacement of the so-called 90°–wall may be responsible for the change in magnetostriction in the course of magnetic after-effect.

In general, there is magnetostrictive energy associated with the domain closure in a ferromagnetic material. This results from the tendency of domain to change slightly in length in the direction of magnetization, so that domains magnetized along different lines will not fit together smoothly except the expenditure of elastic energy in forcing them to fit together. Therefore, the domain closure may be regarded as being squeezed to join to the basic domain, and internal stress may be brought about. Now, the magnetostrictive deformation of material should attend the change in domain structure associated with the displacement of the so-called 90°-domain walls, and therefore, the transitional change in magnetostriction, which takes place after the change in magnetic field is completed, can be related with the delayed displacement of 90°-domain wall so as to reduce excess magnetostrictive energy brought about with the change in domain structure. If magnetostrictive internal stress is able to relax gradually by an activation process aided by thermal agitation, then, according to the theory of recovery, the rate of deformation can be given by the following equation;

$$\frac{d\varepsilon}{dt} = K_0 \exp\left[-\{U - f(1-\varepsilon)\}/kT\right], \tag{1}$$

(2) T. Huzimura, Sci. Rep., RITU, **A 8** (1956), 87, 313.

where $\varepsilon=\Delta l/\Delta l_{t\to\infty}$, U is the activation energy of process, $k$ Boltzmann constant, T absolute temperature and both $K_0$ and f are appropriate constants. By putting

$$K_0\exp\{-(U-f)/kT\}\equiv K_1\,, \tag{2}$$

Eq. (1) changes into

$$\frac{d\varepsilon}{dt}=K_1\exp(-f\varepsilon/kT)\,. \tag{3}$$

By integrating Eq. (3),

$$\varepsilon=\frac{kT}{f}\,ln\left(\frac{t}{t_0}+1\right), \tag{4}$$

where

$$t_0=\frac{kT}{fK_1}\,.$$

If $t\gg t_0$, then

$$\varepsilon\approx\frac{kT}{f}\,(ln\,t-ln\,t_0) \tag{5}$$

The curves of $\varepsilon$ versus log $t$, shown in Fig. 4, fit to the theoretical curve calculated by Eq. (4), taking T=290°K, $t_0$=3.5 sec and f=$1.6\times10^{-13}$ ergs.

The effect of the interaction of the dislocation and the domain was demonstrated by the experiment according to which the motion of dislocation induced a change in the orientation of the domain. The converse effect – the influence of domain on the displacement of dislocation – was found in the study of creep rate in that when the magnetic field was switched on, the creep rate of nickel altered and finally became steady. This converse effect – transient creep accompanied with the change in domain structure – may be attributed to the influence of domain walls on the displacement of dislocations. The magnetoelastic interaction of the stress around dislocation line and the magnetization has been investigated by several workers(3), and it has been pointed out that when a magnetic domain wall passes across a dislocation, the energy due to this interaction varies with its position, and that if this energy change is the main origin of variation of internal energy with the wall position, the dislocation acts as an obstacle on the displacement of the wall through the increase of internal energy as the wall passes across it. The influence of domain wall on the displacement of a dislocation is discussed in Appendix. When a dislocation displaces under the action of shear stress $\tau$, it can pass through a domain wall only when $\tau$ exceeds the critical value which, as described in Appendix, is given by $\lambda$E ($\lambda$ is magnetostriction constant and E Young's modulus) in the order of magnitude.

When the magnitude of magnetostrictive stress can be given by $\lambda$E, the theoretical value of critical shear stress mentioned above is of the same order in

(3) F. Vicena, Czechosl. J. Phys., **5** (1955), 480. T. Huzimura, Trans. JIM, **2** (1961), 182.

magnitude as the magnetostrictive internal stress, i.e. about $5\times 10^2 gr/mm^2$ in the case of nickel. Consequently, it may be concluded that the origin of the after-effect of magnetostriction in the present case is the transient micro-creep under the action of magnetostrictive stress, because micro-creep in nickel has been observed under the stress of several hundred grams per $mm^2$.

## Appendix

Energy of a magnetic domain wall varies with its position as it passes across a dislocation line. When a 180°-domain wall is parallel to (010)-plane and a a dislocation lies in the plane of the wall, the wall energy $\Gamma$ varies with the distance $X_0$ between the dislocation and the midpoint of the domain wall. Theoretical formula of $\Gamma$ has been given in the previous paper[3], in which the curves of $\Gamma$ versus $X_0$ for several cases have been shown. (Figs. 2 and 3). Now, in order to push the dislocation out of the magnetic wall under the action of force F, F should exceed the maximum value of $|d\Gamma/dxo|$. According to our theory, the critical value of F is given by the following expression;

$$F_{cri}=\left|\frac{d\Gamma}{dx_0}\right|_{max.}=\frac{3}{2}\lambda G b\cdot R$$

R is the term which takes a value 0 or 2 depending on the crystallographic orientation of the dislocation line. The critical shear stress $\tau_{cri}$ can be given by

$$\tau_{cri}=\frac{F_{cri}}{b}=\frac{3}{2}\lambda G\cdot R. \quad \text{(a)}$$

For isotropic body, $G\approx E/3$. Therefore, if $E/3$ is substituted for G in Eq. (a) and $R=2$, then $\tau_{cri}=\lambda E$, which is the same expression as that of magnetostrictive stress.

In the case of 90°-domain wall, the wall lies parallel to (101)-plane and the direction of magnetization of domain in either sides of the wall are $\langle 001\rangle$ and $\langle 100\rangle$ direction, respectively; numerical factor in the expression of $\tau_{cri}$ changes to one half of that of Eq. (a). Presumably, although the numerical factor will vary in each case, the formula of $\tau_{cri}$ can be given by the following expression:

$$\tau_{cri}=D\cdot\lambda E \quad (D\leq 1).$$