Behavior of Ferromagnetic Domains under Stress

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The results of some experiments referring to the analogy between the effects of H (uniform magnetic field) and σ (static mechanical stress) on the motion of Weiss domains are described. Together with the results of previous work, the present paper attempts to show the existence of a magnetoelastic Barkhausen effect. A special extensometer with a strain sensitivity of 10^{-7} and completely free from hysteresis was used. Experiments have also been carried out on electrical resistivity variation. The results are summarized as follows: the curves of the remanent strain, $\epsilon_r=(\Delta l/l)_r$ *versus* $\sigma_{\max}$, and of the remanent electrical resistivity variation, $(\Delta\rho/\rho)_r$ *versus* $\sigma_{\max}$, traced for two Ni specimens, one as cast and one annealed, show the same behavior as J_r (remanence magnetization) *versus* $H_{\max}$. Both remanent strain and remanent electrical resistivity variation can be reduced to zero by demagnetizing the specimen. By means of these experiments the characteristic points of the magnetomechanical hysteresis loop have been determined statically and compared with the magnetic case.

1. INTRODUCTION

MOST of the effects of stress on ferromagnetic properties have already been studied by different authors,[1] but it is still worth while to devote some attention to certain aspects of this problem.

As a result of previous work by some of the present authors,[2,3] it may be assumed that a close analogy holds between the effect of stress and magnetic field on domain motion. More precisely, for every ferromagnetic material there exists a characteristic mechanical stress, below which domains behave as in the field of Rayleigh's law; when, on the contrary, the critical value is reached, a true magnetoelastic Barkhausen effect takes place, with irreversible domain jumps followed by a quasi-elastic rotation. The analogy is very close, the only difference being that in the magnetoelastic case the macroscopic intensity of magnetization must obviously remain zero and the orientation of domain magnetization *versus* stress will depend on the sign of the magnetostrictive coefficient, being parallel or perpendicular according to its sign.

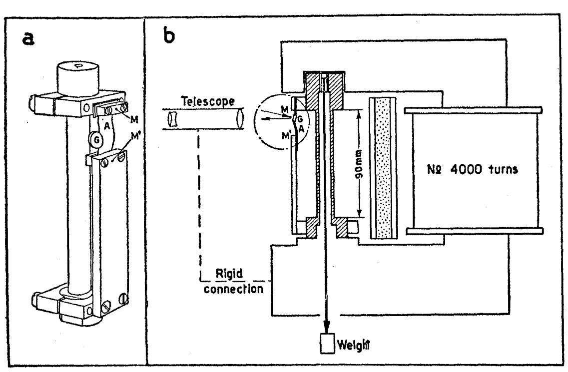

FIG. 1. (a) The specimen with the extensometer mounted on it. (b) Schematic view of the apparatus used.

It should be noted that the magnetoelastic Barkhausen effect has been directly observed by a method strictly analogous to the one for the magnetic case, and described in a paper[4] which was unknown to the writers when their previous work was published. The abovementioned analogy suggests the existence of magnetomechanical energy losses corresponding to those of magnetic hysteresis.

An examination of the literature on the problem of energy losses in mechanical loops of ferromagnetic materials shows that only the field of low stresses has been thoroughly investigated. For the dynamic case, the existence of losses proportional to the frequency of vibration has been shown. For the static case, there exist some papers[5,6] on the "remanent strain" but still in the field of low stress.

As to the results of references 2 and 3, it has been shown that: (a) all the curves of J_r/J_s *versus* σ, δ *versus* σ, and J *versus* H show the same behavior (J= intensity of magnetization, J_s= saturation magnetization, J_r= remanence magnetization, H= magnetic field, σ= mechanical stress, δ= energy losses, J_r/J_s = parameter related to domain distribution); (b) a law similar to the Steinmetz empirical law holds also for the magnetomechanical energy losses; (c) magnetic hysteresis energy losses in a saturation loop are of the same order as magnetoelastic ones (in a mechanical cycle described with a very low frequency, between values of stress not far from the yield point). These measurements have been made with a torsion pendulum.

2. PURPOSE OF PRESENT INVESTIGATION

It seemed that it should be of some interest to investigate these phenomena in the static case, for homogeneous deformation and for stresses high enough to give rise to irreversible domain jumps. Because of experimental difficulties it was impossible to draw directly

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[1] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Co. Inc., New York, 1951), p. 595 ff.
[2] A. Ferro and G. Montalenti, J. Appl. Phys. 22, 565 (1951).
[3] Bonfiglioli, Ferro, and Montalenti, Phys. Rev. 86, 959 (1952).
[4] Toru Kamei, J. Phys. Soc. Japan 6, 260 (1951).
[5] G. Richter, *Probleme der Technische Magnetisierungskurve* (Springer, Berlin, 1938), pp. 93–113.
[6] W. Döring, Ann. Physik 32, 259 (1938).

the magnetomechanical hysteresis loop, as would have been desirable. The scope of the present work is therefore limited to the following points: (a) to show that the remanent strain *versus* σ_{max} after release of a static mechanical stress in pure extension has the same behavior as a magnetization curve; (b) to show that this remanent strain may be reduced to zero by demagnetizing the specimen (by successive hysteresis loops tending to zero): only in this way can we be sure that there are no errors due to plastic deformation; (c) to show that a similar irreversible process exists also with the electrical resistivity.

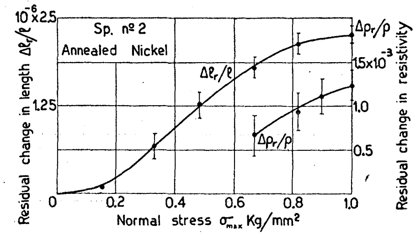

FIG. 3. Curves of remanent strain *versus* maximum stress and of remanent resistivity variation *versus* maximum stress for annealed cast nickel. The uncertainty in the ordinate scale of $\Delta l_r/l$ is about ± 40 percent.

3. DESCRIPTION OF APPARATUS

The equipment used consists of a static test machine, with some particular features to obtain high accuracy in the centering of the load on the specimen by wire suspension, perfect load reproducibility by direct load application, absence of shocks during the charge with an hydraulic device, possibility of applying a magnetic field to the specimen, thermal screening between field

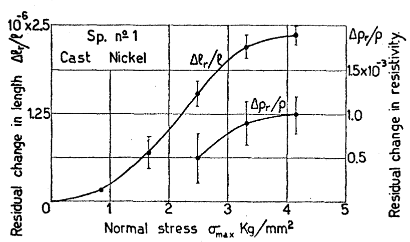

FIG. 2. Curves of remanent strain *versus* maximum stress and of remanent resistivity variation *versus* maximum stress for cast nickel. The uncertainty in the ordinate scale of $\Delta l_r/l$ about ± 40 percent.

wiring and specimen in order to avoid thermal drift, etc. The applied loads are of compression according to the fact that magnetostriction of the specimen is negative.

The extensometer for the strain measurements is of a new type specially designed in order to obtain the necessary very high sensitivity and absolute absence of hysteresis. Since remanent strain is of the order of 10^{-6} a strain sensitivity of 10^{-7} is required. Some initial attempts with other methods such as light fringes or strain gauges were unsuccessful. The main difficulty was to obtain an extensometer completely free from elastic hysteresis even after a large deformation, since the problem was the precise detection of the very little remanent strain in the specimen after the removal of the load. The extensometer shown in Fig. 1(a) consists of a plane phosphor bronze spring A, rigidly clamped to points $M-M'$ and elastically predeformed just beyond the point of flexural instability. A mirror G is rigidly fixed at one fourth of the distance MM', and a light beam reflected on G rotates for an appreciable space when distance MM' is slightly changed. An optical lever with a high-power telescope (equivalent lever length 10 m) allows a sensitivity of about 0.02μ per unit scale.

From measurements on a duraluminum specimen, we observed that this device is entirely free from hysteresis, as stress at A is negligible and all connections are completely rigid. It is, however, evident that such a device is not linear, but calibration may easily overcome such a difficulty. Calibration using as reference the elastic modulus of the specimen must be repeated every time the extensometer is removed from the specimen, as the sensitivity is greatly influenced by the initial MM' distance. Another possible cause of error could have been a defect in axiality of load or homogeneity of material: however, a series of readings taken with the extensometer at 0° and 180° azimuth showed differences always less than 10 percent and therefore not significant to our grade of accuracy. The thermal screening between specimen and field wiring did not give any detectable drift even for periods of time much longer than that required for demagnetizing the specimen.

From the examination of root-mean-square errors of the many series of readings taken during the experiments, we conclude that the reproducibility of measurements within a series of readings is better than ± 10 percent; and that the uncertainty in the absolute calibration of the extensometer is restricted to ± 40 percent. Results may nevertheless be considered satisfactory and allow sufficient reliability as to the description of the phenomenon.

The drawing of Fig. 1(b) shows schematically the equipment used.

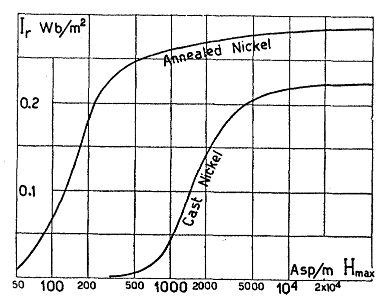

FIG. 4. Curves of remanent magnetization (in webers/meter²) *versus* maximum field (in ampere turns/meter) for cast nickel and annealed nickel.

TABLE I. Comparison of static and dynamic magnetomechanical losses.

Specimen	Saturation magnetic losses (static) joules/m³	$10^6 \cdot \epsilon_r$	σ_{max} kg/mm² (sat. value)	Magnetomechanical losses (static) joules/m³	σ_{max} kg/mm² (sat. value)[a]	Magneto-mechanical losses (dynamic $4H_z$) joules/m³ [a]
Cast Ni	2000	2.30±40%	4.25	104÷416	4	480
Annealed Ni	700	2.25±40%	1	24÷ 96	1	180

[a] From reference 3.

4. RESULTS

The results of the measurements are shown in Figs. 2 and 3. The curves give the remanent strain $\epsilon_r = (\Delta l/l)_r$ and the remanent percent resistivity variation $(\Delta\rho/\rho)_r$ *versus* applied maximum stress. Curves were obtained on Ni specimens: in Fig. 2 for cast Ni and in Fig. 3 for the same Ni annealed. The coercive forces of the two specimens were, respectively, 1200 Asp/m (ampere turns per meter) for the cast nickel and 200 Asp/m for the annealed one. Domain distributions in the specimen are nearly identical and probably nearly isotropic: $J_r/J_s = 0.40$ for specimen No. 1 (cast) and $J_r/J_s = 0.50$ for specimen No. 2 (annealed).

Measurements have been made according to the following scheme: (1) specimen demagnetized (by successive hysteresis loops tending to zero)—unloaded—reading, (2) specimen loaded (till σ_{max}), (3) specimen unloaded—reading, (4) specimen redemagnetized—reading. The length of the specimen in state 4 is practically identical to that in state (1). Taking σ_{max} as abscissa, the corresponding ordinate ϵ_r is given by the difference in length of the specimen between state (1) [or (4)] and state (3). Every experimental point represents an average of 80 readings.

Both curves of remanent strain ϵ_r show a variation of slope for a certain critical stress and for higher values approach saturation: this behavior is strictly analogous to that of the remanent magnetization intensity J_r *versus* maximum field H_{max} and confirms the presence of the magnetoelastic Barkhausen effect (see also the papers quoted[2,3]). (See Fig. 4.) Moreover, in the course of experiments it has been found that the maximum magnetoelastic remanent strain ϵ_r is about $\frac{1}{2}$ of the remanent magnetostrictive deformation measured after the material has been magnetically saturated and then released.

An attempt was also made to verify whether the effect of domain motion on electrical resistivity was analogous. Because of the low resistivity, the large cross section of the specimens, and the great difficulty of getting a good sensitivity, the measurements were not as precise as the ones made on strain. Nevertheless, the curves of Figs. 2 and 3 clearly show that also in this case an irreversible variation of resistivity takes place at a certain critical stress and seems to show a similar behavior. Also, this variation can be reduced to zero by demagnetizing the specimen, and yields about $\frac{1}{2}$ of the remanent magnetoresistivity. We are indebted to Professor A. Drigo for the remark that these results on the electrical resistivity variation seem to give support to the fact that 90° jumps are the principal cause of the effect.

5. EQUIVALENCE BETWEEN FIELD AND STRESS AND COMPARISON WITH MAGNETIC LOSSES

The ratio between coercive forces of the two specimens is nearly identical to the ratio between critical stresses, and the two quantities seem thus to be simply proportional. An attempt was also made to correlate stress with field, using the equations developed by Bozorth[7] and verified for the variations of resistivity on permalloy. By this theory,

$$\sigma = \frac{2}{3}\frac{HJ_s}{\lambda_s} \quad (\lambda_s = \text{saturation magnetostriction}).$$

In our case, assuming $\lambda_s = 34\times10^{-6}$ (see reference 1, p. 659), we have $\sigma = 1$ kg/mm² and therefore $H = 900$ ampere turns/meter, and characteristic points of the curves of ϵ_r *versus* stress should correspond to those of curves of J_r *versus* field: the agreement obtained with these data seems fairly good, especially for cast nickel.

From the values of ϵ_r a rough comparison between static magnetomechanical losses with the dynamic ones can also be made. The order of magnitude of the area of the magnetomechanical loop, by analogy with the corresponding magnetic case for the same material, can be assumed equal to $4\times\frac{2}{3}\times\epsilon_r\times\sigma_{max}$: the approximation with which this value is known may be about ±60 percent; the difficulty of measurement did not allow more accurate values. It is nevertheless possible to confirm the results of a preceding work[3] obtained with damping measurements and to confirm that the magnetomechanical energy losses determined statically or at very low frequency for a stress high enough to obtain magnetomechanical saturation are of the same order of magnitude as the magnetic losses in the saturation loop, the former being nevertheless decidedly inferior (Table I).

[7] R. M. Bozorth, Phys. Rev. **70**, 923 (1946).