THE DEPENDENCE OF THE MAGNETOSTRICTION OF NICKEL UPON INITIAL MAGNETIC TEXTURE AND SEQUENCE OF APPLYING MAGNETIC FIELD AND UNIDIRECTIONAL ELASTIC TENSION

By **J. SHUR** and **A. KHOKHLOV**

Ural Filial of the Academy of Sciences of the USSR, Institute of Metal Physics

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There is studied the influence of initial magnetic texture and of the sequence of applying magnetic field and unidirectional elastic tension on the shape of the curves and the hysteresis loops of the magnetostriction of nickel.

The magnitude of variation of magnetostriction is essentially influenced by the elastic vibrations arising when the load is applied or removed in the presence of a magnetic field. Magnetostriction depends also substantially on the initial magnetic texture of the investigated ferromagnetic body.

1. Introduction

In ferromagnetic bodies subjected to the action of a unidirectional tension there arises a magnetic texture, *i.e.* an anisotropy appears in the spontaneous magnetization distribution along various directions. The character of this texture depends upon the relationship between the sign of magnetostriction and that of the stresses applied to the material. Besides, this magnetic texture is sensitive to the sequence in which the tension and the magnetic field are applied, and likewise depends on the initial magnetic state of the ferromagnetic bodies (1).

The magnetic texture arising with application of elastic tension is retained as long as these stresses remain unchanged. Further a texture of this type shall be called the stable magnetic texture of stresses. If a specimen, in which a magnetic stress texture has arisen, is unloaded, then the given texture becomes unstable, vanishing under the influence of various external factors (magnetic field, elastic vibrations, temperature variations, and so on).

For the study of any type of magnetic structure just as for the present case, valuable information on the character of the magnetic texture under consideration may be furnished by analysing the magnetostriction curves recorded for various magneto-elastic states of the ferromagnetic body. The shape of magnetostriction curves is known to depend upon the distribution of spontaneous magnetization in the initial state of the ferromagnetic body. This dependence is due to the relation between magnetostriction and the manner in which magnetization proceeds. Namely, because of the even character of magnetostriction effects, the displacement of the boundaries between the domains with opposite orientations of magnetization (180° neighbourhood) causes almost no deformation of the material. The displacement of the boundaries between domains with perpendicular orientations of magnetization (90° neighbourhood) results in deformations which determine almost the entire magnitude of magnetostriction in the low field region.

The object of the present work is to investigate the magnetic texture produced in polycrystalline nickel when ferromagnetic is in various ways acted upon by elastic tensions and an external magnetic field. For this purpose the magnetostriction curves, obtained for nickel to which the elastic unidirectional tension and external magnetic field are applied in different sequences, where investigated for different initial magnetic states of the specimen.

2. Specimens tested and method of measurement

All the measurements were made on thin and narrow strips of nickel ($300 \times 0.1 \times 1.3$ mm^3). To minimize internal stresses the specimens prior to measurement underwent a long-time annealing in vacuum at the temperature of 900°C. After the heat treatment the specimens were very carefully mounted into the measurement apparatus.

The magnetostriction measurements were carried out by direct observations of the variation in the specimen dimensions with the optical lever method. A schematic sketch of the device employed in the longitudinal magnetostriction measurements is shown in Fig. 1.

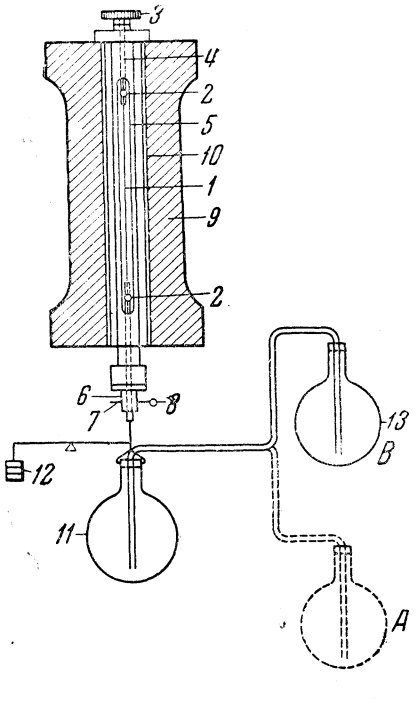

Fig. 1

In this device the specimen to be studied *1* is mounted in the vertical position between clamps *2*. The upper clamp *2* is fixed to screw *4* fitted into head *3*. The use of head *3* enables the specimen to be moved smoothly in the vertical direction. The lower clamp *2*, with the variation in the longitudinal dimensions of the specimen, can be displaced in vertical direction by means of the slides. These slides and screw *4* are rigidly fixed with brass tube *5* having a slit in the middle part. By means of spring *6* the fine tungsten strictly cylindrical wire *7*, to which mirror *8* is soldered, is pressed to the end of the lower clamp *2*. A change in the specimen length in the vertical plane sets the mirror into rotation. Spring *6* is rigidly fixed to tube *5*. The whole apparatus together with the mounted specimen is placed inside solenoid *9* in such a way that head *3* and mirror *8* are kept outside the solenoid. By magnetizing of solenoid *9* a sufficiently uniform magnetic field is produced within a range of 300 mm. Such a uniformity of field was attained by reinforcing the solenoid winding at its ends. The tube of the brass framework of the solenoid *10* was double-walled and served at the same time as a cooling jacket through which water was circulated during measurements in order to maintain constant temperature of the specimen. For the same purpose the holes in the solenoid were closed during measurement in order to prevent air convection. The loading and unloading were performed in the following manner. To lower clamp *2* is suspended a glass bulb *11* connected by means of a rubber tube to vessel *13* filled with water. To exclude entirely the weight of bulb *11*, which is very essential in such measurements, the bulb was attached to one of the beam arms of the scales and was balanced by means of weight *12* attached to the other arm. When vessel *13* is moved up in vertical direction from position *A* to position *B*, and backwards, bulb *11* was filled or emptied, thereby gradually loading or unloading the specimen under test.

3. Measurement procedure

The following course was adopted for making the magnetostriction measurements. First, the specimen to be tested, in order to avoid whatever deformation, was very carefully mounted in clamps *2* (Fig. 1). Further, the whole arrangement with mounted specimen was placed inside magnetizing solenoid *9*. The measurements of magnetostriction started only after complete thermal equilibrium had been established inside the solenoid. All manipulations connected with accomplishing the magnetostriction measurements were carried out with great precaution, avoiding any shaking of the specimen.

In the present measurements of magnetostriction, of interest to us was its variation (due to the different sequence in applying the magnetic field and tension) as these variations are directly related to the magnetic texture formed in the ferromagnetic body. With this aim the following procedure was adopted for making magnetostriction measurements in six different ways.

A. The specimen is gradually demagnetized, then magnetized in a field of a given strength H and the magnetostriction further denoted as λ_0 is measured.

B. The demagnetized specimen is gradually loaded up to a given value of load σ. Thereafter, magnetic field H is applied and magnetostriction measured. This measurement enables to find the change in magnetostriction $\Delta\lambda_1$ due to elastic stresses being applied prior to the magnetic field.

C. After demagnetizing the specimen magnetic field H is applied and only then the specimen is extended under the action of load σ. From the magnetostriction measured in this case its variation $\Delta\lambda_3$ due to elastic tension in the presence of a magnetic field is determined. In determining the value of $\Delta\lambda_3$ the alteration in specimen length due to elastic stresses at $H = 0$ is eliminated.

D. The specimen after demagnetization is gradually loaded up to a given value of load σ. Then magnetic field H is applied, and in the presence of this field H the specimen is gradually unloaded. From the magnetostriction thus measured, its variation $\Delta\lambda_2$ due to the removal of elastic tension in the presence of a magnetic field is determined. In the latter computation the change in the specimen length due to the removal of the elastic tension at $H = 0$ is eliminated.

E. The specimen is demagnetized when stressed by the given load σ. Then the load is relieved, the external magnetic field applied and the measurement of magnetostriction is carried out. From these measurements there is found the variation in magnetostriction due to the alteration in the initial magnetic state produced by demagnetization under load.

In the same manner the hysteresis loops of magnetostriction were recorded, wherefrom the residual magnetostriction λ_r was determined as a function of the initial magnetic state obtained by demagnetizing the specimen under various extensions.

F. The loaded (load σ) specimen is demagnetized and after that the load is gradually released. Then it is again gradually loaded, the magnetic field switched on and the magnitude of magnetostriction is measured. From these measurements there is found the variation in magnetostriction $\Delta\lambda_4$, due to the elastic tension applied prior to the magnetic field, the specimen having been preliminarily demagnetized in the extended state.

4. Results of measurements

The results of measuring the magnetostriction of nickel in the six aforesaid ways are given in Figs. 2—9.

In Fig. 2a are presented magnetostriction curves taken for a nickel specimen after its demagnetization in unloaded state with different extension loads applied during mea-

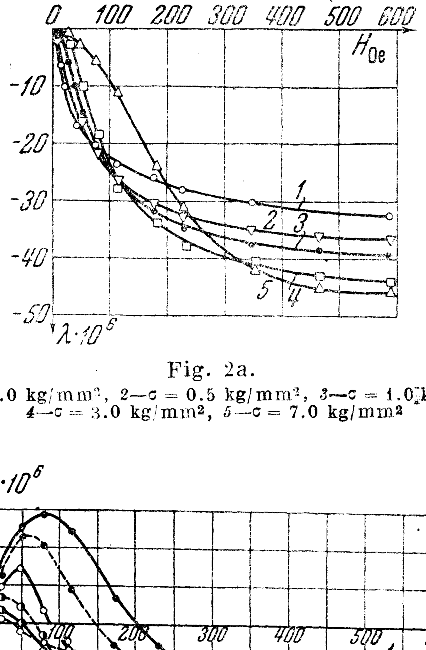

Fig. 2a.

1—σ — 0.0 kg/mm^2, 2—σ = 0.5 kg/mm^2, 3—σ = 1.0 kg/mm^2, 4—σ = 3.0 kg/mm^2, 5—σ = 7.0 kg/mm^2

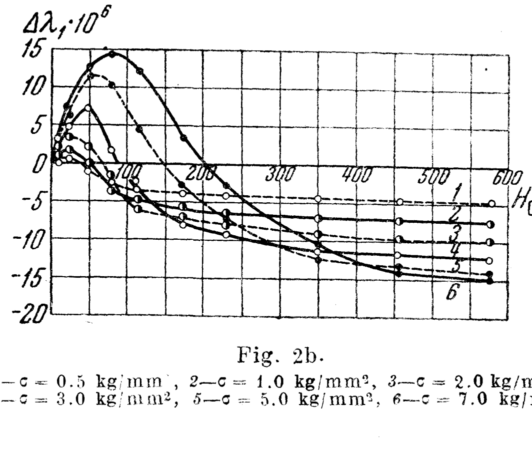

Fig. 2b.

1—σ = 0.5 kg/mm, 2—σ = 1.0 kg/mm^2, 3—σ = 2.0 kg/mm^2, 4—σ = 3.0 kg/mm^2, 5—σ = 5.0 kg/mm^3, 6—σ = 7.0 kg/mm^2

surement. [Method B; curve $\lambda(H)$ with $\sigma = 0$ was obtained by method A]. From Fig. 2b it is seen that, when the load is applied prior to the magnetic field, the magnetostriction in the initial portions of the curves diminishes in absolute magnitude $\Delta\lambda_1 > 0$. The field strength range, where $\Delta\lambda_1 > 0$, increases with increasing load σ.

In the higher field region the quantity $\Delta\lambda_1$ changes its sign, becomes negative and increases in absolute magnitude with increasing load.

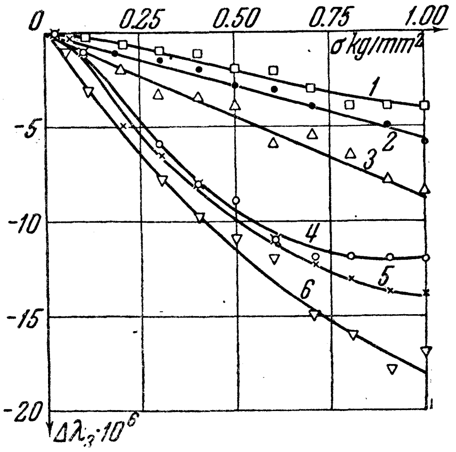

Fig. 3

1—H = 0.2 Oe, 2—H = 0.4 Oe, 3—H=2.3 Oe, 4—H=4.5 Oe, 5—H = 11.5 Oe, 6—H = 23.0 Oe

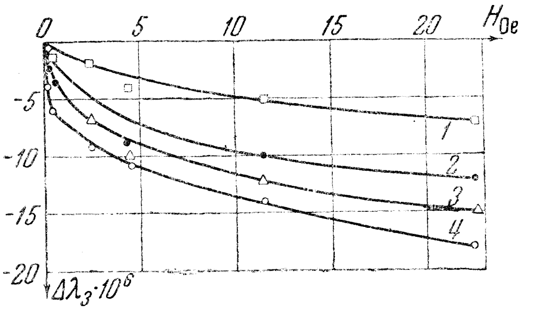

Fig. 4

1—σ = 0.2 kg/mm², 2—σ = 0.5 kg/mm², 3—σ = 0.7 kg/mm², 4—σ = 1.0 kg/mm²

In Figs. 3 and 4 are given the values of the variation in magnetostriction $\Delta\lambda_3$ measured after the load is applied in the presence of the magnetic field (method C). As is seen from these curves, the negative magnetostriction of nickel with such sequence of applying the magnetic field and load increases in absolute magnitude the more the larger is the tension (Fig. 4) and the magnetic field (Fig. 3).

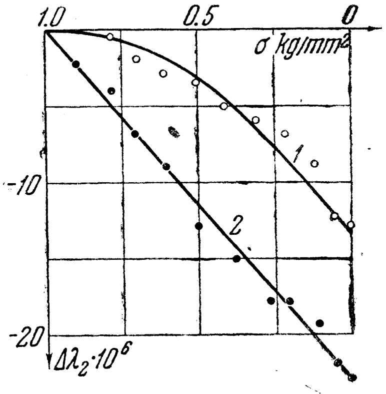

Fig. 5

1—H = 4.5 Oe, 2—H = 11.5 Oe

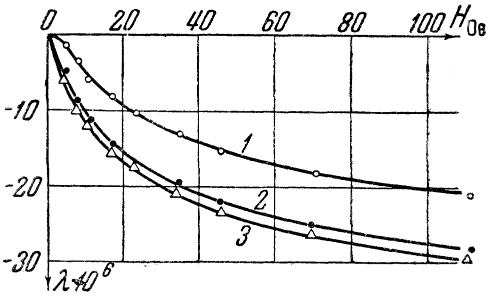

Fig. 6

1—σ_{dem} = 0 kg/mm², 2—σ_{dem} = 1 kg/mm², 3—σ_{dem} = 2 kg/mm²

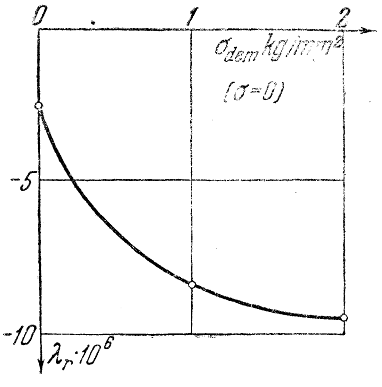

Fig. 7

In Fig. 5 are given the curves showing the relation between variation in magnetostriction $\Delta\lambda_2$ and the load removed in the presence of field ($H = 4.5$ and $H = 11.5$ Oe). On the abscissae axis are plotted the values of the remaining load σ. From these curves it is seen that with load removed in the presence of the magnetic field the negative magnetostriction of nickel increases in absolute magnitude ($\Delta\lambda_2 < 0$), the increase being the greater the larger are the removed load and the magnetic field during the unloading operation (method D).

In Fig. 6 are presented the magnetostriction curves for a loaded specimen with various initial magnetic states produced by demagnetizing the specimen under different extending loads (method E). Comparison of these curves demonstrates that with rising load $\sigma_{\rm dem}$ applied during demagnetization, the negative magnetostriction only increases in absolute magnitude for all values of magnetic fields.

Most influenced by the variation in initial magnetic states, produced by means of demagnetization under various loads, is the value of residual magnetostriction (method E).

Fig. 7 shows the dependence of residual magnetostriction upon the magnitude of the load $\sigma_{\rm dem}$ applied during the demagnetization. From this curve it is seen that as the load $\sigma_{\rm dem}$ is increased the absolute magnitude of residual magnetostriction increases.

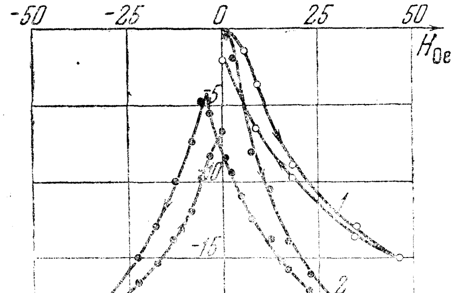

Fig. 8.
1—$\sigma_{\rm dem} = 0$ kg/mm², 2—$\sigma_{\rm dem} = 1.0$ kg/mm²

In Fig. 8 are given the maximum hysteresis loops of magnetostriction obtained with a specimen after demagnetizing it under load $\sigma_{\rm dem} = 0$ and $\sigma_{\rm dem} = 1$ kg/mm². In fields above 50 Oe the magnetostriction hysteresis vanishes.

And finally, in Figs. 9a and 9b is shown the effect of tension on the magnetostriction curves of a nickel specimen that was submitted to demagnetization under the load $\sigma_{\rm dem} = 1$ kg/mm² (method F). The comparison of the curves in Fig. 9a and in Fig. 2a shows that the influence of elastic extension on the magnetostriction curve does not change also for a specimen that underwent preliminary demagnetization under the load.

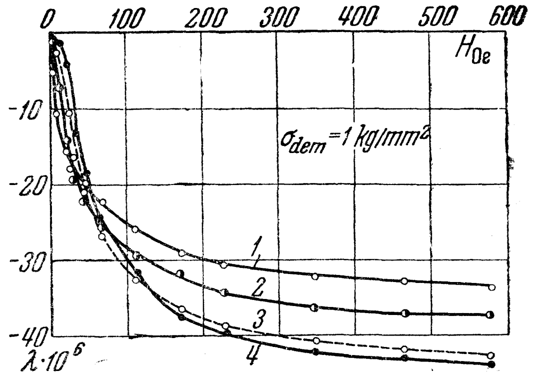

Fig. 9a.
1—$\sigma = 0$ kg/mm², 2—$\sigma = 1$ kg/mm², 3—$\sigma = 2$ kg/mm², 4—$\sigma = 3$ kg/mm²

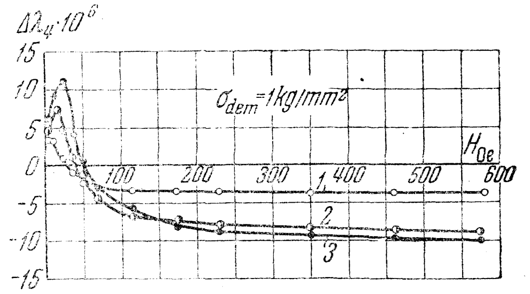

Fig. 9b.
1—$\sigma = 1$ kg/mm², 2—$\sigma = 2$ kg/mm², 3—$\sigma = 3$ kg/mm²

5. Analysis of measurement results

A demagnetized ferromagnetic body is known to have the disposition of boundaries between domains and the orientation of their spontaneous magnetization vectors I_s intimately related to the distribution of internal stresses in the material (²). Therefore, any redistribution of internal stresses must inevitably give rise to new stable configurations of domains. One of the methods for producing a redistribution of internal stresses in an unmagnetized ferromagnetic body is to submit the specimen to unidirectional elastic extension or compression by an external force.

As a consequence of any change in the magnitude of the external force, there arise in the magnetic material elastic vibrations which determine the kinetics of the redistribution of internal stresses in the material and, therefore, the kinetics of establishing of a new magnetic texture. After these vibrations have died down, there sets in a new equilibrium distribution of internal stresses and a magnetic texture appropriate to it. This equilibrium state, however, will not always be absolutely stable but sometimes might be metastable. The presence of such metastable states may lead to a non-uniqueness of magnetostriction, *i. e.*, to the irreversible phenomena of magnetostriction hysteresis.

The influence exerted by the external magnetic field depends essentially upon initial magnetic state of the ferromagnetic body. Therefore, it should be expected that if a unidirectional load is applied to or removed from a specimen, either being already under the action of an external magnetic field or prior to its putting on, there result different variations in the magnetostriction. And therefore, with the same magnetic field strengths and elastic stresses substantially different values of the magnetostriction may be obtained, *i. e.* a magneto-elastic hysteresis of magnetostriction occurs.

Based on these conceptions our experimental results lend the following qualitative explanation.

A. Load applied to nickel specimen prior to putting on a magnetic field

In this case, when the load rises an increasing number of domains acquire the vector orientation I_s close to the plane perpendicular to the directions of the acting load and magnetizing field. Upon formation of such a texture (for which almost all domains with a magnetization oriented along the magnetic field vanish), the contributions made both by the 180° and the 90° displacements of the domain boundaries decrease considerably. This effect of gradual relative reduction of the displacements processes with rising loads is especially distinctly pronounced in the well investigated phenomenon of the deformation of magnetostriction curves of nickel under the action of extension (3). As is seen from Fig. 2, magnetostriction in the high field region increases in absolute magnitude with rising tension. This increase in magnetostriction is due to the fact that the diminution in specimen length during the transition from demagnetized state to that of magnetic saturation (the magnetostriction of saturation λ_s) varies depending upon the degree of magnetic texture. Thus, for instance, upon transition from the state of magnetic isotropy to that of maximum magnetic textures of extension (all the vectors I_s of the domains lie in the plane normal to the line of extension) the saturation magnetostriction of nickel rises 1.5 times in absolute magnitude (3). As is seen from Fig. 2 this limiting increase of λ_s is already nearly attained with an extension load $\sigma=7$ kg/mm².

In the low field region the relative reduction of the displacement processes, due to elastic tension, must result in a decreased absolute magnitude of magnetostriction. In this case magnetostriction is contributed primarily by rotation processes which for the development of the same magnetostriction require stronger fields than in the case of an unstretched specimen where magnetostriction is due to displacement processes. Hence it follows that with increasing load the field interval is increased on the initial part of the curves, where the absolute magnitude of magnetostriction diminishes ($\Delta\lambda_1>0$). This inference is fully supported by the course of the curves in Figs. 2a and 2b.

B. Load applied to nickel specimen in the presence of a magnetic field

When the magnetic field and the load are applied in the above mentioned sequence, the elastic extension of the specimen results in appearance of new stable positions of the domain boundaries. The transition of the domain boundaries to these more stable equilibrium states occurs, firstly, in the presence of a magnetic field tending to enhance the displacement of those boundaries which increase the volumes of the domains with I_s orientated nearly along the direction of the field, and, secondly, in the presence of stresses tending, in opposition to the magnetic field, to orientate vectors I_s along the directions perpendicular to the line of extension.

In our experiments (small loads) with specimens stressed in presence of magnetic field the predominating influence on the variation of the magnetostriction of the nickel specimen was apparently that exerted by the magnetic field. From the curves in Figs. 3 and 4 it is seen that for loads up to $\sigma = 1$ kg/mm^2 the magnetostriction increases in absolute magnitude. Meanwhile this increase of magnetostriction rises, firstly, with increasing magnetic field, and, secondly, with increasing load. The latter is evidently accounted for by the greater elastic stresses resulting in displacement of a greater number of domain boundaries. This transition of the boundaries to stable states is mainly used by the magnetic field, for the absolute magnitude of the extending stresses is insufficient to overcome the action of the magnetic field.

C. Load released from nickel specimen in the presence of a magnetic field

In this case the magnetic field alone makes use of the displacement of the domain boundaries caused by removal of load. The greater the load relieved, the greater the number of domain boundaries turning unstable. Consequently, in this case magnetostriction must only increase in absolute magnitude with rising value of released load and rising magnetic field. This rise in magnetostriction is actually observed experimentally (Fig. 5). In this case there should be observed a greater change in magnetostriction than in the previous case, since the magnetic field and stresses produce effects of the same sign. Comparison of the curves in Figs. 4 and 5 shows this inference to agree with the experimental data. Namely, with one and the same magnetic field of 11.5 Oe, the loading of the specimen with 1 kg/mm^2 produces negative magnetostriction, $\Delta\lambda_3 = -14 \cdot 10^{6}$ (Fig. 4), and the removal of the same load produces $\Delta\lambda_2 = -24 \cdot 10^{-6}$ (Fig. 5), *i. e.* $|\Delta\lambda_2| > |\Delta\lambda_3|$.

D. Nickel specimen demagnetized under extending load

As known (4), the demagnetization of ferromagnetic bodies, when loaded unidirectionally, results in the formation of a magnetic texture. The appearance of such a texture is due to the fact that unidirectional load, applied in the course of demagnetizing, assists in the formation of domains with spontaneous magnetization oriented along the line of stretching (for materials with $\lambda > 0$) or in the plane perpendicular to this line ($\lambda < 0$).

In the nickel specimens ($\lambda < 0$) the magnetic texture, appearing after demagnetization under load, is of the last type. The appearance of such a texture is best detectable from the deformation of the magnetostriction curves obtained after demagnetizing the loaded specimen. This deformation of the magnetostriction curves should be reducible to an increase in the absolute value of the saturation magnetostriction at the expense of the increase in the initial demagnetized state of the volume occupied by domains with vectors I_s directed perpendicularly to the direction of the magnetizing field, just as it occurs after the elastic stresses are applied (Fig. 2). However, in the weak field region, in contradistinction to the magnetostriction curves taken under extension, there is no diminution in the absolute magnitude of magnetostriction in the initial part of the curves. This is because the considered magnetic texture becomes unstable after the load, with which demagnetization proceeded, is relieved. Therefore, the increase of magnetization in the initial portion of the curve occurs mainly at the expense of displacing the "unstable" boundary domains, which leads only to an increase of the absolute magnitude of magnetostriction. These conclusions are confirmed by the magnetostriction curves obtained with a specimen demagnetized under various loads (Fig. 6).

Under the action of elastic stresses applied to a nickel specimen that has been preliminarily demagnetized under load, the magnetic texture becomes the more stable, the larger the load applied during the measurement. In the weak field region the appearance of such stability in the magnetic texture should result in the absolute magnitude of magnetostriction falling off with increasing load applied during the magnetostriction measurement. This reduction in magnetostriction was detected experimentally (Fig. 9).

The increase in the absolute magnitude of magnetostriction with rising load applied during the measurement in the strong field region, as observed on the curves $\lambda(H)$ of Fig. 9, is less than for the corresponding curves given in Fig. 2. This distinction in the magnitude of the change in magnetostriction, occurring in the strong field region under action of extension detected by comparing the curves of Figs. 9 and 2, is due to the distinction in the initial demagnetized states.

In recording the hysteresis loops of magnetostriction a sharp increase of the residual magnetostriction is to be expected with the rise of the load at which the specimen undergoes preliminary demagnetization. Indeed, after demagnetization under load the magnetostriction saturation increases. But after this saturation is attained the "unstable" magnetic texture obtained on demagnetization completely disappears and the variation of magnetostriction along the descending branch of the hysteresis loop ($\lambda_s - \lambda_r$) should not depend on the initial demagnetized state, *i. e.*

$$(\lambda_s - \lambda_r)_{\sigma_{\text{dem}}=0} = (\lambda_s - \lambda_r)_{\sigma_{\text{dem}}>0},$$

whence it follows that

$$(\lambda_r)_{\sigma_{\text{dem}}>0} - (\lambda_r)_{\sigma_{\text{dem}}=0} =$$

$$= (\lambda_s)_{\sigma_{\text{dem}}>0} - (\lambda_s)_{\sigma_{\text{dem}}=0}.$$

Thus the change in the residual magnetostriction must equal the corresponding change in the magnetostriction saturation. This relationship is fully substantiated by experiment, as is readily seen from comparing the hysteresis loops in Fig. 8 taken at $\sigma_{\text{dem}} = 0$ and $\sigma_{\text{dem}} = 1$ kg/mm^2:

$$(\lambda_r)_{\sigma_{\text{dem}}=1} - (\lambda_r)_{\sigma_{\text{dem}}=0} =$$

$$= (7.9 - 2.0)\,10^{-6} = 5.9 \cdot 10^{-6};$$

$$(\lambda_{H=47})_{\sigma_{\text{dem}}=1} - (\lambda_{H=47})_{\sigma_{\text{dem}}=0} =$$

$$= (21.0 - 15.0)\,10^{-6} = 6.0 \cdot 10^{-6}.$$

Conclusion

The main results of the experimental data, obtained in the present investigation on the influence of elastic stresses on the magnetostriction curves of nickel, are as follows:

1. For the first time there has been studied the influence of the initial magnetic texture and of the sequence, in which the magnetic field and the load are put on, on the shape of the curves and hysteresis loops of magnetostriction of a ferromagnetic body.

2. These data enable to arrive at the following inferences as to the influence of the elastic stress, texture and of the initial magnetic state on the magnetostriction of nickel.

The value of the change in magnetostriction is influenced essentially by the elastic vibrations that arise when the load is applied or relieved in presence of magnetic field. Namely:

In absolute magnitude the magnetostriction of nickel, when acted upon by these elastic vibrations, only increases.

The value of magnetostriction of nickel depends essentially upon the magnetic texture of the initial magnetic state. Namely:

After the loaded specimen has been demagnetized, the magnetostriction of nickel increases in absolute magnitude throughout the whole interval of field strengths right up to saturation.

The deformation of the magnetostriction curves after demagnetization under load when acted upon by elastic extension is less than after demagnetization without load.

The value of the residual magnetostriction increases with the rise of the load acting during the demagnetization. This increase of residual magnetostriction is equal to the corresponding increase in the saturation value of magnetostriction.

On the basis of modern conceptions as to the processes of technical magnetization, a qualitative theoretical interpretation is offered for experimental results.

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