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ELECTRICAL AND MAGNETIC PROPERTIES

On the Origin of Peaks of Differential Magnetic Permeability in Low-Carbon Steels after Plastic Deformation

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Abstract—The physical origin of peaks in the field dependence of differential magnetic permeability of low-carbon steels after their plastic tensile deformation have been theoretically studied; they are caused by the irreversible displacements of the 90° domain walls. The angular difference between the [100] axes of the two neighboring grains with the large-angle boundaries has been determined; it corresponds to the peaks of differential permeability. It also controls the value of residual compressive stress. The results obtained are in perfect agreement with the corresponding experimental data.

Keywords: differential magnetic permeability, magnetization, descending branch of hysteresis loop, magnetic-anisotropy energy, magnetoelastic energy, magnetic-field energy, angular difference between axes of neighboring grains, large-angle boundaries, small-angle boundaries

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INTRODUCTION

It was shown in [1–3] that the plastic tensile deformation and subsequent unloading of steels lead to the appearance of large compressive stresses in some grains (up to (0.7–0.8) $\sigma_Y(\varepsilon_{pl})$), where $\sigma_Y(\varepsilon_{pl})$ is the yield stress in the hardening region at a certain strain ε_{pl}. These stresses are linearly polarized along the direction of tensile load (the magnetic field $\mathbf{H_0}$ is applied exactly along this direction).

As a result of plastic deformation, the magnetic texture of an easy-plane type (EP) occurs in such grains, which abruptly changes the values of all magnetic parameters, e.g., coercivity [4] and remanence [5], as well as the field dependence of differential magnetic permeability, $\mu_d(H_0)$ [6].

Numerous experimental works (see, e.g., [2, 3, 5, 7]) have shown that the dependence of differential permeability $\mu_d(H_0)$ of the steel "St3" after its plastic tensile deformation has two peaks in the descending branch of hysteresis loop (when the strength of magnetic field H_0 decreases after reaching the saturation magnetization M_S), i.e., at $H_0 = H_1 > 0$ and $H_0 = H_2 < 0$. The positions and amplitudes of the peaks can serve as control parameters of internal stresses. The problem of the physical origin of these peaks is therefore a relevant one for modern researchers. The solution of this problem will allow concurrent questions to be resolved, e.g., which grains are characterized by the residual compressive stresses? How do these stresses correlate with the fields corresponding to the peaks of $\mu_d(H_0)$? How many of these peaks are there? The last question is caused by the fact that with decreasing magnetic field along the descending branch of hysteresis loop three irreversible transitions have to occur, i.e., 90°, at $H_0 > 0$; 180°, at low negative fields; and 90°, at the negative magnetic fields of higher magnitudes [5–7].

This work is devoted to these questions.

EXPERIMENTAL DATA

In [6], the $\mu_d(H_0)$ curves were measured for the St3-steel samples subjected to the tensile deformation with ε_{pl} 8.4 and 2.1% at $\sigma_0 = 0$ (σ_0 is an applied tensile stress) and at $\sigma_0 = |\sigma_i^m|$ (σ_i^m is the maximum value of σ_i). The analysis of these curves allowed for the development of a method for distinguishing the contribution of the irreversible displacements of the 90° domain walls (DWs) to the differential permeability $\mu_d^{90}(H_0)$.

In this work, we will explain the physical origin of the peaks of differential permeability based on these curves, without demonstrating them.

ON THE ORIGIN OF THE PEAKS OF $\mu_d^{90}(H_0)$

First, let us consider the formation of the peaks of $\mu_d^{90}(H_0)$. It evidently occurs in grains with residual compressive stresses aligned with the direction of the tensile load. Such first-order stresses [8] can occur only in grains with large-angle boundaries (LABs) [9] after unloading the tensile deformation.

Note that the boundary between two grains is considered to be the LAB, if the minimum angular difference $\Delta\theta$ between their [100] axes exceeds the characteristic value $\Delta\theta_{LAB}$, i.e., $\Delta\theta_{LAB} \le \Delta\theta \le 55°$ ($\Delta\theta = 55°$ is the maximum angle possible in the case of crystals with cubic symmetry and bcc lattice). If $\Delta\theta \le \Delta\theta_{LAB}$, the boundary is the small-angle boundary (SAB) [8]. The effects of the LAB grains on the occurrence of the large internal stresses in the polycrystalline steels have been mentioned in a number of works (see, e.g., [10–12]).

Here, it is important that in the case of the SAB grains, under the first-order stresses [10], dislocations move into the neighboring grain, which is equivalent to the sliding of the boundary between the grains [9]. In the case of the LAB grains, such sliding is not observed [9], which is the necessary condition for the occurrence of residual compressive stresses $\sigma_i < 0$ after unloading the plastically deformed steel. These stresses are observed in one of two grains, which has higher Young modulus in the direction of load (as well as magnetic field) [8]. In this case, the residual compressive stresses occur, which originate from the difference in the Young moduli and the strain after unloading:

$$\sigma_i(\varepsilon_{\rm pl}) = -\varepsilon_{\rm unl}\left[E(\theta_2) - E(\theta_1)\right]; \qquad \varepsilon_{\rm unl} = \sigma_{\rm Y}(\varepsilon_{\rm pl})/\bar{E}, \tag{1}$$

where $\varepsilon_{\rm unl}$ is the strain after unloading [9], $\bar{E}$ is the average Young modulus of the isotropic steel. Evidently, Eq. (1) demonstrates that the sufficient condition for the occurrence of the stresses is the Young modulus anisotropy in each of the steel grains. In the case of iron it is sufficiently large, i.e., according to [13] $E_{111} = 2.1E_{100}$.

Another important factor is the isotropic distribution of the [100] easy axes of steel grains after annealing, which results in the maximal number of the LAB grains. Any texture decreases this number.

Following [3, 5], we use the following linear approximation of the $E(\theta)$ dependence:

$$E(\theta) = E_{100} + \gamma\theta, \tag{2}$$

which has an error of 4%; γ is the constant independent of θ.

From relationships (1) and (2) we derive

$$\sigma_i(\varepsilon_{\rm pl}) = \varepsilon_{\rm unl}\gamma(|\theta_1 - \theta_2|) = \varepsilon_{\rm unl}\gamma|\Delta\theta|. \tag{3}$$

Coefficient ($\varepsilon_{\rm unl}\gamma$) can be determined as follows: according to Eqs. (1), (3), at $\Delta\theta = 55°$, we should observe the maximum value of the residual stresses $\sigma_i = \sigma_i^{\rm m}$. The value of $\sigma_i^{\rm m}$ is experimentally determined from the dependence of coercivity on the elastic tensile stresses [3], i.e., it has been found that at $\varepsilon_{\rm pl}$ = 8.4%, $\left|\sigma_i^{\rm m}\right|$ = 295 MPa; at $\varepsilon_{\rm pl}$ = 2.1%, $\left|\sigma_i^{\rm m}\right|$ = 240 MPa.

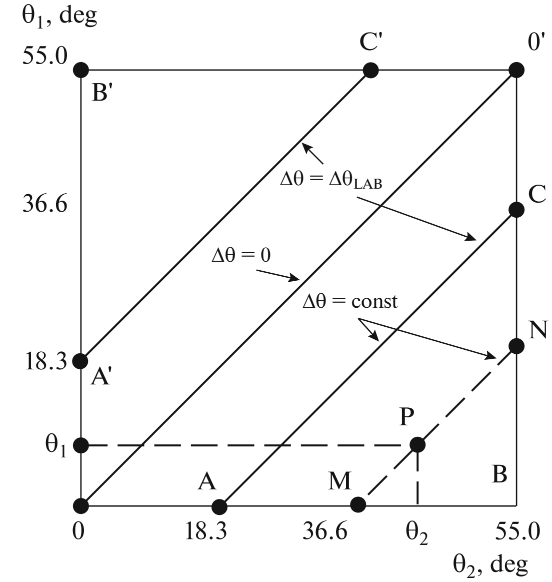

Fig. 1. Neighborhood diagram of two grains of steel with the angular difference between their [100] axes equal to $|\theta_2 - \theta_1|$.

The strain after unloading $\varepsilon_{\rm unl}$ is also taken from the experiment [3, 13], where $\sigma_{\rm Y}(2.1\%)$ = 360 MPa, $\sigma_{\rm Y}(\varepsilon = 8.4\%)$ = 460 MPa, $\bar{E} = 2.17 \times 10^5$ MPa. Considering the linear dependence of stresses σ_i on $\Delta\theta$ (3) and the maximum value of σ_i at $\Delta\theta = 55°$, values of the ($\varepsilon_{\rm unl}\gamma$) coefficient can be found for the strains of 2.1 and 8.4%. Thus, we obtain the exact expressions which correlate the internal stresses to $\Delta\theta$ for certain values of plastic deformation:

$$\sigma_i(8.4\%) = -5.36|\Delta\theta|, \text{ MPa}; \qquad \sigma_i(2.1\%) = -4.76|\Delta\theta|, \text{ MPa}. \tag{4}$$

The magnetoelastic field H_σ also linearly depends on $\Delta\theta$ [3, 5]:

$$H_\sigma = (1.5\lambda_{100}\sigma_i/M_{\rm s}) = (1.5\lambda_{100}\varepsilon_{\rm unl}\gamma|\Delta\theta|)/M_{\rm s}, \tag{5}$$

where λ_{100} is the magnetostriction constant for iron, $M_{\rm s}$ = 1600 A/cm is the saturation magnetization of the St3 steel. From (4) and (5) we derive:

$$H_\sigma^{\rm theor}(8.4\%) = -0.8|\Delta\theta|, \text{ A/cm}; \qquad H_\sigma^{\rm theor}(2.1\%) = -0.7|\Delta\theta|, \text{ A/cm}. \tag{6}$$

From (4), it follows that the values of the residual compressive stresses linearly decrease with decreasing $\Delta\theta$.

Let us analyze how the number of compressed grains changes in this case. To this end, consider two adjacent grains with angles θ_1 and θ_2 between their [100] axes. Figure 1 shows a diagram in coordinates of angles θ_1 and θ_2 (each of the angles varies in the range of 0°–55°). Each point of the diagram represents two adjacent grains of steel; and any region of the diagram designates their number. Thus, the SAB grains are located between straight lines AC and A'C' (see Fig. 1). The LAB grains are located in the ABC and A'B'C' triangles; the relative number of grains is proportional to the area of the triangles. If $\Delta\theta_{LAB}$ values are known, this number can be easily calculated.

The maximum possible number of such grains is proportional to the area of each of the ABC and A'B'C' triangles (see Fig. 1):

$$N(\Delta\theta_{LAB}) = 0.5(55° - \Delta\theta_{LAB})^2. \tag{7}$$

In the case of intermediate values of $\Delta\theta$ ($\Delta\theta_{LAB} \leq \Delta\theta \leq 55°$), the number of compressed grains characterized by irreversible magnetization jumps to 90° is still determined by expression (7), where $\Delta\theta_{LAB}$ should be replaced by $\Delta\theta$.

Both these processes (the linear decrease of H_σ and square increase in the number of compressed grains with decreasing $\Delta\theta$) control the value of the irreversible changes in magnetization due to jumps of the 90° DWs, and, consequently, the differential permeability $\mu_d(H_0)$. Therefore, in the first approximation, which does not consider the effects of potential barriers of the 90° domain walls [6], $\mu_d(H_0)$ has to be proportional to the following function:

$$F(\Delta\theta) = a\Delta\theta N(\Delta\theta) = a\Delta\theta(55° - \Delta\theta)^2, \tag{8}$$

where a is the coefficient independent of $\Delta\theta$. Function (8) has a maximum at

$$\Delta\theta_{theor} = 18.33°. \tag{9}$$

Consequently, this value has to be equal to $\Delta\theta_{LAB}$, because if $\Delta\theta \leq \Delta\theta_{LAB}$, after unloading the plastically deformed steel, the compressive stresses do not occur (see discussion above), and, therefore, the differential permeability in this region $\Delta\theta$ must decrease. In other words, the peak of $\mu_d(H_0)$ has to always occur at $\Delta\theta = \Delta\theta_{LAB}$.

Now, let us consider the correction of (9), caused by the barriers for the irreversible jumps of the 90° DWs ($H_B^{90} M_s$). In this case, the change in magnetization at the 90-degree jump $\Delta M_{90}(\theta_0)$ (θ_0 is the angle between the field and the nearest [100] axis)

$$\Delta M_{90}(\theta_0) = M_s(\cos\theta_0 - \sin\theta_0) \tag{10}$$

can be determined with the aid of the equation for 90° jumps [3, 6]

$$-H_0(\cos\theta_0 - \sin\theta_0) + |H_\sigma|\cos 2\theta_0 = H_B^{90}. \tag{11}$$

Thus, for the 90° jump in a compressed grain with a certain value of θ_0, we obtain:

$$\Delta M_{90}(\theta_0) = \left(|H_\sigma|\cos 2\theta_0 - H_B^{90}\right) M_s / H_0. \tag{12}$$

Substituting Eq. (6) for H_σ, we obtain that $\Delta M_{90}(\theta_0)$ linearly depends on $\Delta\theta$. If we now consider the entire ensemble of the compressed grains with the LABs with different values of $\Delta\theta$, then to calculate the total change in the magnetization due to the 90-degree jumps, expression (12) has to be multiplied by the $N(\Delta\theta)$ function described by Eq. (7). Then,

$$\Delta M_{90}(\theta_0, \Delta\theta) = \left(0.8\Delta\theta\cos 2\theta_0 - H_B^{90}\right) \times (55° - \Delta\theta)^2 M_s/(2H_0). \tag{13}$$

Here, H_σ is expressed in terms of $\Delta\theta$ according to (6) for ε_{pl} = 8.4%; in addition, we use the experimental value for $H_B^{90} = 0.64$ A/cm [6].

Then, by minimizing (13) with respect to $\Delta\theta$, we can find a more precise value of $\Delta\theta_{theor}$, which corresponds to the maximum of ΔM_{90} and, consequently, to the maximal contribution to the differential permeability $\mu_d^{90}(H_0)$, which is provided by the 90° jumps. As a result, we obtain

$$\Delta\theta_{theor} = 19°. \tag{14}$$

This value differs from that approximated by Eq. (9) only by 3.6%, which falls within the limit of the above-applied approximation for $E(\theta)$. Thus, according to Eqs. (4), (6), the peaks of $\mu_d^{90}(H_0)$ correspond to the stresses σ_i^{theor} and magnetoelastic fields H_σ^{theor} calculated with this error:

$$\begin{gathered} \sigma_i^{theor}(2.1\%) = -87.2 \text{ MPa}; \\ H_\sigma^{theor}(2.1\%) = -13.0 \text{ A/cm}; \\ \sigma_i^{theor}(8.4\%) = -98.3 \text{ MPa}; \\ H_\sigma^{theor}(8.4\%) = -14.7 \text{ A/cm}. \end{gathered} \tag{15}$$

Since in modern metallographic methods, such as the EBSD analysis, the value of the angle $\Delta\theta_{theor}$ = 18.33° (9) (or $\Delta\theta_{theor}$ = 19° (14)) is determined with an error of 2%, thus, it is more practical to assume its value to be $\Delta\theta_{theor} = \Delta\theta_{LAB} = (18° \pm 1°)$ [8, 13, 14], rather than 18.33° (or 19°).

Therefore, with decreasing H_0 along the descending branch of the hysteresis loop, the 90° jumps start to occur in the most compressed grains with $\Delta\theta$ = 55° in the H_0 fields of an order of $H_\sigma^m = H_\sigma^{theor}$ ($\Delta\theta$ = 55°). For example, for ε_{pl} = 8.4%, from (6) we derive $H_\sigma^m(8.4\%) = 44$ A/cm. Upon further decrease of $H_0 <$ 44 A/cm, the irreversible jumps of the 90° DWs will occur at lower fields, which in this case will be accompanied by the linear increase in the number of residually compressed grains until its value of $\Delta\theta_{LAB}$ is reached; the latter corresponds to the maximum possible number of compressed grains controlling the intensity of the differential-permeability peak.

EXPERIMENTAL CONFIRMATION OF THEORETICAL CONCLUSIONS

In [3, 5, 6,], the equations for the fields corresponding to both peaks of $\mu_d^{90}(H_0)$, which are valid for any angle θ_0 (between the field and the nearest [100] axis in any steel grain), are derived by analyzing the sum of the magnetic anisotropy energy, magnetoelastic energy, and energy in the H_0 field:

$$\begin{aligned} H_{cr}^{90}(H_0 > 0) &= |H_\sigma|(\cos\theta_0 + \sin\theta_0) \\ &- H_B^{90}/(\cos\theta_0 - \sin\theta_0); \\ H_{cr}^{90}(H_0 < 0) &= -|H_\sigma|(\cos\theta_0 + \sin\theta_0) \\ &- H_B^{90}/(\cos\theta_0 + \sin\theta_0). \end{aligned} \tag{16}$$

Specifying the fields $H_{cr}^{90}(H_0 > 0)$ and $H_{cr}^{90}(H_0 < 0)$ equal to the experimental values $H_1^* > 0$ and $H_2^* < 0$ [6], we can derive from Eq. (16) the corresponding values of angles θ_0, which are equal to $|\Delta\theta|$ at $\theta_1 = 0$.

An experimental method was developed in [6] of evaluating the fields H_1^* and H_2^*, corresponding to the peaks of $\mu_d^{90}(H_0)$ which can be only caused by the irreversible displacement of the 90° DWs. The total differential magnetic permeability $\mu_d^{90}(H_0)$, i.e., the sum of $\mu_d^{90}(H_0)$ and $\mu_d^{180}(H_0)$, has two peaks in the fields $H_1 > 0$ and $H_2 < 0$; these fields differ from H_1^* and H_2^* and thus cannot be used to determine internal stresses.

The method developed in [6] suggests the application to the plastically deformed steel sample of the elastic tensile stress to compensate the internal compressive stresses (up to the maximum value $\sigma_0 = |\sigma_i^m|$). Then, the obtained curve $\mu_d^{180}(H_0, \sigma_0)$ with one peak at $H_0 < 0$ was subtracted from the initial curve $\mu_d(H_0, \sigma_0 = 0)$; as a result, we obtained the curve with three extrema, two of which corresponded to the 90° transitions in the fields $H_1^* > 0$ and $H_2^* < 0$ and one, to the 180° transition in the field H_{cr}^{180}.

Thus, fields H_1^* and H_2^* were determined experimentally. If the second equation of (16) is subtracted from the first one, the barrier-field term H_B^{90} will be excluded as follows:

$$H_1^* - H_2^* = 2|H_\sigma|(\cos\theta_0 + \sin\theta_0). \tag{17}$$

As a result, for known values of the fields H_1^* and H_2^*, the corresponding value of the magnetoelastic field H_σ^{exp} can be found as follows:

$$H_\sigma^{exp} = \left(H_1^* - H_2^*\right)\Big/[2(\cos\theta_0 + \sin\theta_0)]. \tag{18}$$

For the sake of clarity, the calculations will be conducted for the steel sample with $\varepsilon_{pl} = 8.4\%$, in which according to [6] $H_1^* = 17.5$ A/cm; $H_2^* = -19.4$ A/cm. Specifying H_σ^{exp} equal to H_σ^{theor}, from Eqs. (6) and (18) we obtain the following equation

$$0.8\Delta\theta = 18.45/(\cos\Delta\theta + \sin\Delta\theta), \tag{19}$$

thus, at $\theta_0 = |\Delta\theta|$ (see the discussion above) we, finally, obtain

$$\Delta\theta_{exp} = 18.3° = \Delta\theta_{theor} = \Delta\theta_{LAB}. \tag{20}$$

According to (6), this value corresponds to the field value $H_\sigma^{exp}(8.4\%) = -14.7$ A/cm. The same procedure can be carried out for the case of $\varepsilon_{pl} = 2.1\%$. The result will be the same, i.e., $\Delta\theta_{exp} = 18.3°$.

The fact that the $\mu_d^{90}(H_0)$ peak has to be located at the boundary of small- and large-angle grains of steel allows us to state that the relationship $\Delta\theta_{exp} = \Delta\theta_{LAB}$ derived above is valid. Thus, this value is obtained from magnetic measurements.

METALLOGRAPHIC CONFIRMATION OF THE VALUE $\Delta\theta_{LAB} = 19°$

It is well known that (see, e.g., [17, 18]) the minimum of the grain boundary energy corresponds to the angle of turn of the crystal lattices of the neighboring grains around the [100] axis [17, 18] by 36.9°. In this case, the coincident site lattice (CSL) corresponds to the densely packed plane of the adjacent grains ((110) for bcc-metals, to which the St3 steel belongs). Therefore, in the case of the symmetric boundary, the angle between the normal to the CSL plane and the [100] direction in each of the two grains under consideration is 18.4°.

We can therefore conclude that the value of $\Delta\theta = 18° \pm 1°$, which was obtained in this work and in [6] with the aid of magnetic measurements and corresponds to the occurrence of the residual stresses, represents the special boundaries with the coincident-site density $\Sigma = 5$ [17, 18].

This conclusion is also proved by the neighborhood diagram of two grains (see Fig. 1), where the angle between the directions $\theta_2 = 18.33°$ and $\theta_1 = 18.33°$ is equal to 36.66°, which is close to 36.9°.

Note that the value of $\Delta\theta_{LAB} = 18° \pm 1°$ obtained in this work is affected by the fact that in our case in each LAB grain, the easy axis of magnetization and the direction of the minimal Young modulus coincided with the [100] axes. This fact explains why the value of $\Delta\theta_{LAB}$ obtained in this work is two times less than the angle between the normals to the planes with the maximal density of sites, i.e., 36.9°.

CONCLUSIONS

(1) We obtained the value of the angular difference between the axes of the neighboring grains with large-angle boundaries; it corresponds to the peaks in the field dependence of differential permeability, which are caused by the jumps of the 90° domain walls. This angular difference is $\Delta\theta_{exp} = 18.33°$.

(2) We determined the angular difference between the adjacent grains; it controls the value of magnetoelastic field and residual stress in the field, which correlate with this difference and correspond to the peak of the differential permeability upon magnetization reversal of the low-carbon ferromagnetic steel St3 along the descending branch of the hysteresis loop. These values are almost the same as the corresponding experimental ones [6]. We have also shown that maximal values of the residual compressive stresses are three times higher than those of the stresses corresponding to the peak of differential permeability.

(3) The origin of the peaks of differential permeability is that, with decreasing difference in angles of the adjacent grains from the maximum value of 55°, the value of the residual compressive stresses linearly lowers. At the same time, the number of compressed grains of steel, in which the irreversible 90° jumps occur increase by a square law. As a result the value of magnetization change caused by the 90° jumps is maximal at $\Delta\theta_{theor} = 18° \pm 1°$.

(4) The boundary between the grains of the plastically deformed steel with large- and small-angle boundary grains was determined by magnetic measurements.

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