ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2018, Vol. 54, No. 12, pp. 855–860. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.N. Stashkov, V.G. Kuleev, E.A. Shchapova, A.P. Nichipuruk, 2018, published in Defektoskopiya, 2018, No. 12, pp. 37–42.

ELECTROMAGNETIC METHODS

Studying Field Dependence of Reversible Magnetic Permeability in Plastically Deformed Low-Carbon Steels

A. N. Stashkov[a], *, V. G. Kuleev[a], **, E. A. Shchapova[a], *, and A. P. Nichipuruk[a], ******

[a]Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620108 Russia

*e-mail: stashkov@imp.uran.ru

**e-mail: kulejevv@imp.uran.ru

***e-mail: katyuhazhul@mail.ru

****e-mail: nichip@imp.uran.ru

Received July 12, 2018

Abstract—The field dependences of the signal $U^{\sim}(H)$ across the measuring winding of an induction transducer, which are proportional to reversible magnetic permeability, have been measured in low-carbon St3 steel plastically deformed by stretching under reversal of its magnetization along the major hysteresis loop both when unloaded and under an elastic tensile load. A method is proposed for isolating the contribution rendered to the measured signal by the irreversible displacement of only 90-degree domain walls. The method consists in subtracting the curve $U^{\sim}(H)$ measured under the elastic tensile load of a magnitude sufficient to compensate for internal compressive residual stresses in the sample from the no-load $U^{\sim}(H)$ curve. It has been established that the induced magnetic anisotropy field obtained with this method is virtually no different from that produced by the method in which no-load $U^{\sim}(H)$ curves are approximated.

Keywords: steel, mechanical stresses, anisotropy, induction transducer, aligned magnetic fields, reversible magnetic permeability, induced magnetic anisotropy field

DOI: 10.1134/S1061830918120094

INTRODUCTION

Plastic stretching of low-carbon steels brings about residual compressive stresses σ_i aligned in the direction of load in some of the grains with high-angle boundaries [1]. These stresses affect magnetic and magnetoacoustic properties of steel [2–11], but often in an ambiguous way because under reversal of magnetization in ferromagnets, the displacements of both 90- and 180-degree domain walls (DWs) jointly affect the resulting value of a magnetic parameter. Therefore, when monitoring mechanical stresses, it is very important to single out contributions due to only 90-degree domain walls, which are most sensitive to stresses. In [12, 13], the authors succeeded in experimentally separating contributions from the two types of domain walls and proposed a method for determining the value of induced magnetic anisotropy, which is a measure of mechanical stresses. An original primary transducer was described in [13], which was an attached electromagnet (AEM) equipped with an induction transducer placed in the interpole space. In this work, the field dependences of the e.m.f. $U^{\sim}(H)$ in the pickup coil of the induction transducer were obtained under an orthogonal scheme of magnetization reversal in St20 steel plates. The AEM generated the magnetization-reversal field at a local spot of the test article, while the bias field was created by the excitation coil of the induction transducer. Since two rather than three maxima were observed on experimental $U^{\sim}(H)$ curves [13], the experimental data were subjected to additional mathematical treatment to calculate the magnetic-anisotropy field strength, viz., the dependences $U^{\sim}(H)$ were approximated by three curves with single maxima, using pseudo-Voigt functions. To calculate the induced magnetic anisotropy field H_a, we used fields, corresponding to the maxima of two curves, in which displacements of 90-degree domain walls predominantly occurred [13]. Having the value of H_a known, the internal mechanical stresses were calculated. Comparison with a test experiment, in which the sample was

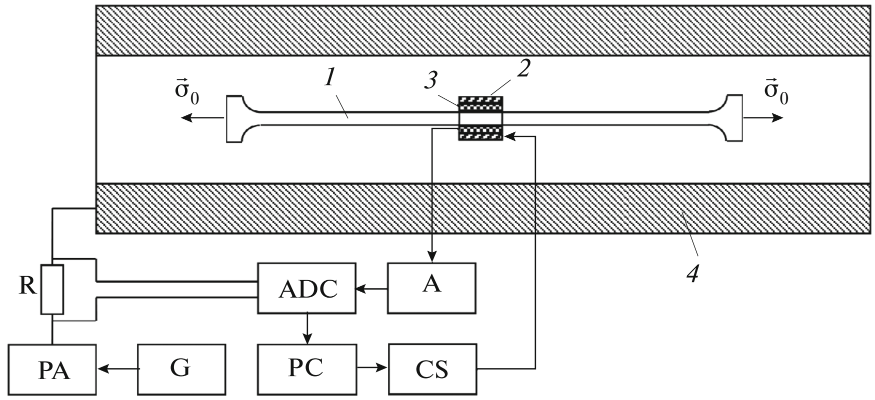

Fig. 1. Experimental setup: (*1*) sample; (*2*) bias coil; (*3*) pickup coil; (*4*) solenoid; A amplifier; G generator; PA power amplifier; CS alternating-current source; ADC analog-to-digital converter; PC personal computer.

elastically compressed, showed that the result was satisfactory. However, the procedure of approximating the $U^{\sim}(H)$ curves complicated the processing of experimental data and was not easily amenable to automation, needed when developing magnetometric facilities. Therefore, it was necessary to find an alternative way of processing experimental data. Moreover, a question arose related to the orthogonality of the magnetizing and bias fields, namely, is this condition mandatory for separately detecting the fields of the irreversible displacement of 90- and 180-degree domain walls?

The objectives of this study are:

• given a homogeneous magnetization-reversal field and an aligned variable magnetizing field, to establish whether the field of anisotropy induced by mechanical stresses can be determined experimentally;

• to develop a technique for experimentally determining the positions of peaks on the $U^{\sim}(H)$ curve that correspond to the irreversible displacement of 90-degree domain walls, which are most sensitive to mechanical stresses, without resorting to complex mathematical operations.

EXPERIMENTAL

Similar to [14], experimental studies were performed using 267-mm-long specimens of mild St3 steel with a cross section of 2×3 mm^2, which, after annealing in vacuum at 650°C for two hours and subsequent slow furnace cooling, were plastically stretched to ε_{pl} equal to 2.1 and 8.4%.

The setup for measuring the field dependences of the e.m.f. $U^{\sim}(H)$ was different from that described in [14]; its scheme is presented in Fig. 1. Instead of a differential coil, two (excitation and measuring) coils were arranged on the sample; hereinafter, we will call them induction transducer. An alternating current with a frequency of 30 Hz was fed into the winding of the excitation coil. The pickup coil signal was detected at the frequency of the alternating current. The reversal of magnetization in the samples along the major hysteresis loop was carried out in a solenoid at the field variation frequency 5×10^{-3} Hz field; the maximum magnetic field strength in the solenoid was ±135 A/cm.

The ends of the samples were fixed in the grips of a mechanical test machine for applying elastic tensile stresses σ_0 during magnetic measurements. The field dependences of the e.m.f. $U^{\sim}(H)$ were measured with no load, as well as when a uniaxial tensile load was applied to the sample in order to eliminate the contribution from the irreversible displacement of 90-degree DWs.

RESULTS AND DISCUSSION

As the amplitude of the bias field *h* created by the induction transducer's excitation coil is much lower than the coercive force of tested samples, the e.m.f. of the measuring winding of the induction transducer was considered to be proportional to the reversible magnetic permeability μ_{rev}.

The displacements of 90-degree domain walls (which we are interested in) due to a variable field h gives rise to a variable magnetization $m_{90}(t)$ and, therefore, the e.m.f. $U^{\sim}(H,t)$

$$U^{\sim}(H,t) = A\left(\frac{d}{dt}\right)[m_{90}(H,t)] = A\omega m_{90}(H,t) = \omega h(t)\mu_{\text{rev}}(H,t), \tag{1}$$

where ω is the circular frequency of the alternating bias field; t is time; and A is a coefficient independent of H and t and defined, for example, by the number of turns in the pickup coil, gaps, etc.

As a result, the dependence of the e.m.f. in the pickup coil of the induction transducer on the field and time is proportional to the reversible permeability $\mu_{\text{rev}}(H,t)$.

Recall that with decreasing the bias field from saturation along the back of the hysteresis loop, two maxima were observed on the field dependences of differential magnetic permeability $\mu_d(H)$ [14]. The first and second peaks are located in the domains of positive and negative fields, respectively. It was shown in [14] that the shape of the resulting curve $\mu_d(H)$, especially the position of its negative-field maximum, is affected by the irreversible displacements of both 90- and 180-degree DWs

$$\mu_d(H_0) = \mu_d^{90}(H_0) + \mu_d^{180}(H_0). \tag{2}$$

It is impossible to separate contributions from permeabilities μ_d^{90} and μ_d^{180}, hence we failed to determine the field of the induced magnetic anisotropy and residual stresses based on the resulting curve $\mu_d(H)$. In this regard, a method was developed in [14] to isolate the contribution from the irreversible displacement of only 90-degree DWs. To this end, the strained St3-steel specimen was subjected to elastic tensile stresses σ_0 of a magnitude sufficient to compensate for the largest residual compressive stresses σ_i^m. The value of σ_i^m was determined based on a minimum exhibited by the dependence of coercive force on elastic tensile stresses [15]. As a result, we obtained a curve $\mu_d(H)$ with only one peak due to the irreversible displacements of only 180-degree DWs, i.e., the quantitty $\mu_d\left(H,\sigma_0 = \left|\sigma_i^m\right|\right)$, equal to the differential permeability in Eq. (2). This curve $\mu_d\left(H,\sigma_0 = \left|\sigma_i^m\right|\right)$ was then subtracted from the original curve $\mu_d(H,\sigma_0 = 0)$ to obtain the curve

$$\Delta\mu_d(H,\varepsilon_{\text{pl}}) = \mu_d(H,\sigma_0 = 0) - \mu_d\left(H,\sigma_0 = \left|\sigma_i^m\right|\right), \tag{3}$$

having three extrema, which fully corresponds to the sequence of irreversible transitions of magnetization with a decrease in the field along the back of the hysteresis loop: first, an irreversible 90-degree transition from angle θ_0 to angle $(\theta_0 - 90°)$ occurred in the field $H > 0$; then an irreversible 180-degree transition occurred (from angle $(\theta_0 - 90°)$ to angle $[(\theta_0 - 90°) + 180°]$) in the field $H < 0$; and, finally, with a further decrease in the field, an irreversible transition to angle $\{[(\theta_0 - 90°) + 180°] + 90°\}$. The physical nature of the three extrema on the curve $\Delta\mu_d(H,\varepsilon_{\text{pl}})$ was explained in [16]; here θ_0 is the angle between the field and the nearest type-[100] axis of the given grain. Due to an isotropic distribution of grains in steel after its annealing, approximately equal numbers of grains corresponded to each value of θ_0.

As a result, the fields of the right and left peaks H_1^* and H_2^* on curve $\Delta\mu_d(H,\varepsilon_{\text{pl}})$ were determined in [14]. Using these fields and the well-known equation for irreversible transitions of 90-degree DWs, the induced magnetic anisotropy field H_{a} (magnetoelastic field H_σ^*) was determined, and mechanical stresses σ_i were calculated as

$$\sigma_i = (1.5\ \lambda_{100}\ H_{\text{a}})/M_s, \tag{4}$$

where λ_{100} is the magnetostrictive constant of iron and M_s is the saturation magnetization.

In the present work, we applied the procedure proposed in [14] to isolate three extrema that correspond to the irreversible displacements of different types of DWs, but as applied to the field dependences of the e.m.f. in the pickup coil of the induction transducer. To this end, field dependences $U^{\sim}(H)$ were measured for samples with ε_{pl} equal to 2.1 and 8.4% with no load and when applying the elastic tensile load of a magnitude that was selected for each sample based on the condition of creating maximum stresses to compensate for internal residual ones. Figure 2 shows experimental curves $U^{\sim}(H)$ obtained on St3-steel

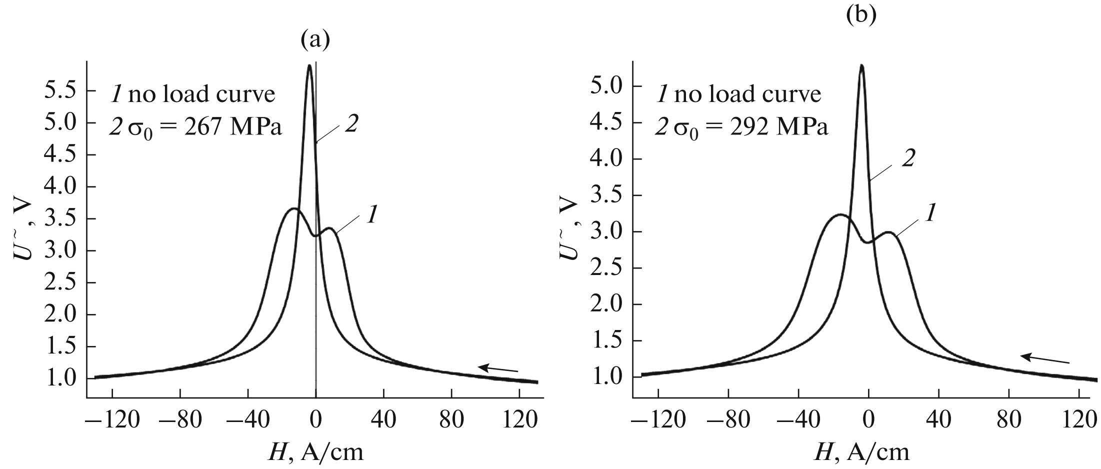

Fig. 2. Field dependences of e.m.f. in pickup coil, measured on samples of mild St3 steel [(a) ε_{pl} = 2.1, (b) ε_{pl} = 8,4%]. Curves (*1*) were obtained for samples with no external load, curves (*2*) with an external tensile load applied.

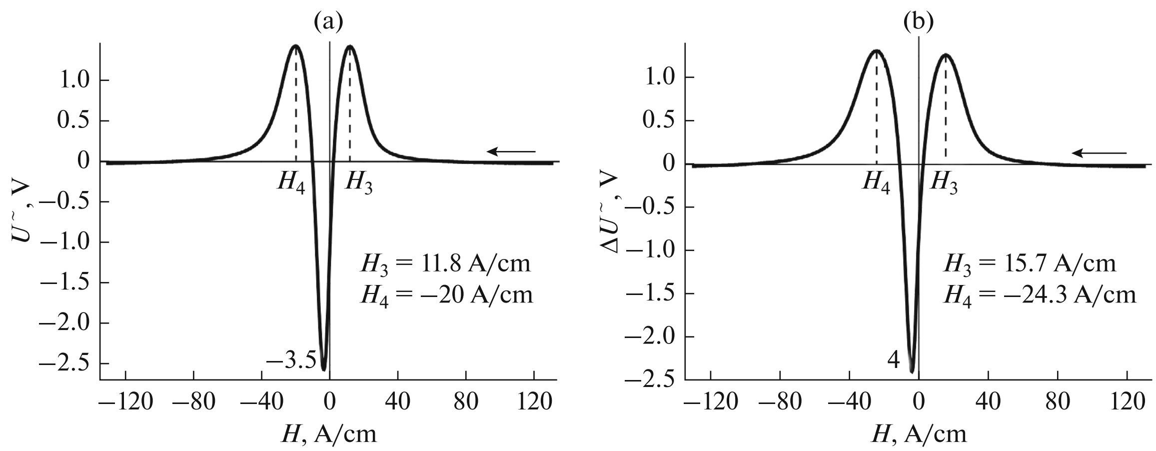

Fig. 3. Field dependences of e.m.f. in pickup coil, obtained by subtracting curves (*2*) from curves (*1*) (see Fig. 1) for plastically deformed samples with relative elongations of (a) 2.1 and (b) 8.4%.

samples with ε_{pl} equal to 2.1 (Fig. 2a) and 8.4% (Fig. 2b) in the unloaded state ($\sigma_0 = 0$, curves *1*), and curves *2* under conditions of tensile stresses $\sigma_0 = \left|\sigma_i^m\right|$ applied.

Without the application of elastic stresses $\sigma_0 = 0$, curve *1* (Figs. 2a and 2b) exhibits two maxima, in positive and negative fields. A similar pattern was observed in some of the previous works (see, for example, [14, 16]), but the fields of these maxima are not suitable for obtaining the actual value and distribution of σ_i for the same reasons as indicated above for the case of experimental curves $\mu_d(H)$.

Elastic tensile stresses $\sigma_0 = \left|\sigma_i^m(\varepsilon_{pl})\right|$ were applied to the samples, with single negative-field maxima observed on measured curves *2* (Figs. 2a and 2b). Further, curves *2* were subtracted from curves *1* similar to the condition in Eq. (3) for differential magnetic permeability, with the results presented in Figs. 3a and 3b for the samples with ε_{pl} equal to 2.1 and 8.4%, respectively. As in [14], these curves have three extrema, of which we are interested only in two outermost ones, caused by the irreversible displacements of 90-degree DWs.

We denote the fields of these extrema by $H_3 > 0$ and $H_4 < 0$. As an example, let us provide data for the sample with ε_{pl} = 8.4%: H_3 and H_4 are 15.7 and –24.3 A/cm, respectively. In the case of differential per-

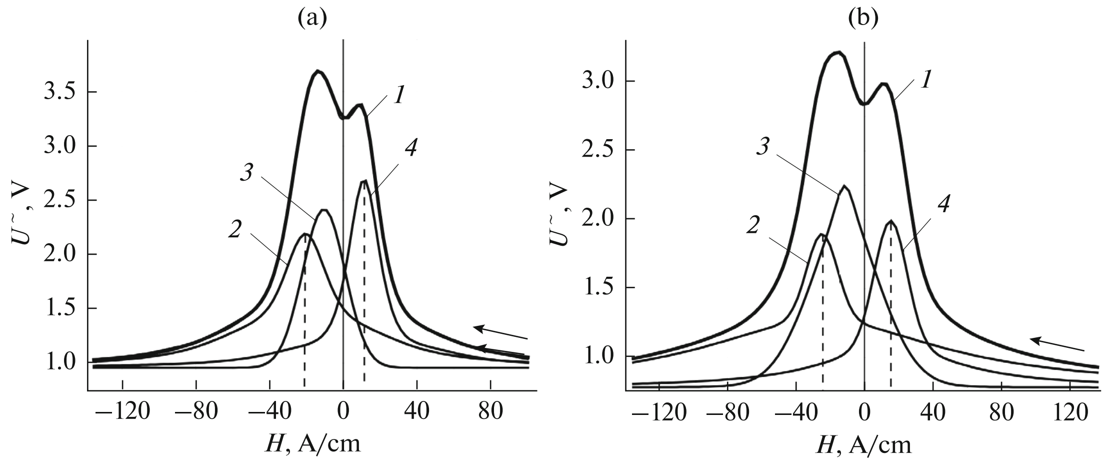

Fig. 4. Experimental data and approximation results for plastically deformed samples with relative elongations of (a) 2.1 and (b) 8.4%: (*1*) experimental curve; (*2–4*) curves with single maxima after approximation.

meability [14], the fields of the corresponding maxima H_1^* and H_2^* were 17.5 and −19.4 A/cm. We see that the fields H_3 and H_4 differ significantly in magnitude from the fields H_1^* and H_2^*, moreover,

$$H_3 < H_1^*; |H_4| > \left|H_2^*\right|. \tag{5}$$

Interestingly, this difference takes place despite the fact that the cause of peaks on dependences $\mu_d^{90}(H)$ and $U^{\sim}(H)$ is the same, viz., an increase of residually compressed grains with decreasing $\Delta\theta$ until $\Delta\theta = \theta_{HAB}$, combined with a linear decrease in stresses $\sigma_i < \Delta\theta$ [16].

Due to the difference in peak fields noted in Eq. (5), determining the values and $\Delta\theta$-distribution of residual stresses in the case of reversible permeability $\mu_{rev}(H)$ ($U^{\sim}(H)$) must obey another algorithm than in the case of $\mu_d(H)$ [14, 16]. This problem should be solved in a separate paper, considering the specific features of the reversible vibrations of 90-degree DWs in plastically deformed low-carbon steels.

In [13], we proposed a method for processing experimental data that consists in approximating the initial $U^{\sim}(H)$ curve with three single-maximum curves using pseudo-Voigt functions. In this work, such a treatment was also carried out for samples with the relative elongations of 2.1 and 8.4% (Fig. 4).

The fields of the maxima of curves *2* and *4* were 11.2 and −20.5 A/cm for the sample with $\varepsilon = 2.1\%$, while for the sample with $\varepsilon = 8.4\%$ they were 15.3 and −24.7 A/cm. The values of the fields of the maxima obtained after approximation differ from those shown in Fig. 3 by no more than 5.3%, with the arithmetic mean values of the fields (i.e., fields of stress-induced magnetic anisotropy) deviating by no more than 0.3%. Thus, this method, based on subtracting two dependences $U^{\sim}(H)$ (with no load and under an elastic tensile load), is an alternative to the previously proposed one, which consists in approximating experimental curves.

CONCLUSIONS

(1) The field dependences of the e.m.f. $U^{\sim}(H)$ in the pickup coil of an induction transducer have been measured in a homogeneous magnetization-reversal field and an aligned variable bias field. It has been established that $U^{\sim}(H)$ curves for plastically deformed samples of mild St3 steel exhibit two maxima, one in a negative field and the other in positive.

(2) A method is proposed for determining field values that correspond to irreversible displacement of 90-degree domain walls based on experimental curves $U^{\sim}(H)$. The method consists in subtracting the curve measured with such an applied tensile load that compensates for internal residual stresses in the

sample from the curve measured with no external load. The positions of the determined fields of extrema on the resulting curve can be used to determine the induced magnetic anisotropy field (or magnetoelastic field) and residual stresses.

(3) Comparing the proposed method with the method based on approximating initial dependences $U^{\sim}(H)$ using three pseudo-Voigt functions has demonstrated that the difference in the field maxima does not exceed 5.3% and that in their arithmetic means, 0.3%.

(4) It has been established that the fields of maxima on dependence $U^{\sim}(H)$ accounted for by the displacements of only 90-degree domain walls differ in their magnitude from the fields of the corresponding maxima on dependence $\mu^{d}(H)$. Finding out the reason of the differences should be addressed in a separate paper.

ACKNOWLEDGMENTS

This work was carried out within the framework of the state order from the FASO of the Russian Federation (the topic "Diagnostics", project no. AAAA-A18-118020690196-3).

REFERENCES

1. Nichipuruk, A.P., Stashkov, A.N., Kostin, V.N., and Korkh, M.K., Possibilities of magnetic inspection of plastic deformations preceding failures of low-carbon steels constructions, *Russ. J. Nondestr. Test.,* 2009, vol. 45, no. 9, pp. 616–622.
2. Bozorth, R.M., *Ferromagnetism,* Wiley-IEEE Press, 1993.
3. Chikazumi, S., *Physics of Ferromagnetism,* Oxford Univ. Press, 1997, 2nd Ed.
4. Shcherbinin, V.E. and Gorkunov, E.S., *Magnitnye metody strukturnogo analiza i nerazrushayushchego kontrolya* (Magnetic Methods of Structural Analysis and Nondestructive Testing) Yekaterinburg: Ural Branch, Russ. Acad. Sci., 1996.
5. Schajer, G.S., *Practical Residual Stress Measurement Methods,* Vancouver: John Wiley & Sons Ltd., 2013.
6. Kuleev, V.G., Tsar'kova, T.P., Sazhina, E.Y., and Doroshek, A.S., On the influence of plastic deformations of low-carbon ferromagnetic steels on the changes in the shapes of their hysteresis loops and the field dependences of the differential permeability, *Russ. J. Nondestr. Test.,* 2015, vol. 51, no. 12, pp. 738–749.
7. Gorkunov, E.S., Povolotskaya, A.M., Zadvorkin, S.M., and Putilova, E.A., Comparative analysis of the magnetic characteristics of plastically deformed metal in different zones of a welded pipe under elastic deformation, *Russ. J. Nondestr. Test.,* 2017, vol. 53, no. 9, pp. 636–643.
8. Kostin, V.N., Vasilenko, O.N., Filatenkov, D.Y., Chekasina, Y.A., and Serbin, E.D., Magnetic and magnetoacoustic testing parameters of the stressed–strained state of carbon steels that were subjected to a cold plastic deformation and annealing, *Russ. J. Nondestr. Test.,* 2015, vol. 51, no. 10, pp. 624–632.
9. Murav'ev, V.V., Volkova, L.V., Platunov, A.V., and Kulikov, V.A., An electromagnetic-acoustic method for studying stress-strain states of rails, *Russ. J. Nondestr. Test.,* 2016, vol. 52, no. 7, pp. 370–376.
10. Kulak, S.M. and Novikov, V.F., Control of mechanical stresses in steel frames and structures experiencing multiaxial strains, *Kontrol' Diagn.,* 2016, no. 5, pp. 55–60.
11. Bulte, D.P. and Langman, R.A., Origins of the magnetomechanical effect, *J. Magn. Magn. Mater.,* 2002, vol. 251, pp. 229–243.
12. Nichipuruk, A.P., Rozenfel'd, E.V., Ogneva, M.S., Stashkov, A.N., and Korolev, A.V., An experimental method for evaluating the critical fields of moving domain boundaries in plastically tension-deformed low-carbon wires, *Russ. J. Nondestr. Test.,* 2014, vol. 50, no. 10, pp. 566–573.
13. Nichipuruk, A.P., Stashkov, A.N., Kuleev, V.G., Schapova, E.A., and Osipov, A.A., A procedure and device for calibration-free determination of residual compression stresses in low-carbon steels deformed by tension, *Russ. J. Nondestr. Test.,* 2017, vol. 53, no. 11, pp. 772–778.
14. Kuleev, V.G., Stashkov, A.N., Tsar'kova, T.P., and Nichipuruk, A.P., Experimental determination of critical fields of 90-degree domain wall displacement in plastically deformed low-carbon steels, *Russ. J. Nondestr. Test.,* 2018, vol. 54, no. 10 (in press).
15. Kuleev, V.G. and Tsar'kova, T.P., Effect of plastic deformations and heat treatment on the behavior of the coercive force under load, *Phys. Metals Metallogr.,* 2007, vol. 104, no. 5, pp. 461–468.
16. Kuleev, V.G., Degtyarev, M.V., Stashkov, A.N., and Nichipuruk, A.P., On the physical nature of peaks of differential magnetic permeability in plastically deformed low carbon steels, *Phys. Metals Metallogr.,* 2019, vol. 120, no. 1 (in press).

Translated by V. Potapchouck