ELECTROMAGNETIC METHODS

Dedicated to the memory of our fellow countryman Academician
Gorkunov Eduard Stepanovich, who began his scientific and
pedagogical activities at the Industrial Institute of Tyumen.
Eduard Stepanovich was one of the initiators of the direction
being developed in the proposed article [1].

Relationship between Magnetoelastic Sensitivity of Magnetoelastic Demagnetization of Steels 60G and 65G and Coercive Force and Magnetostriction

V. F. Novikov[a],*, S. M. Kulak[a],**, K. R. Muratov[a],***, and A. S. Parakhin[a],****

[a] *Tyumen Industrial University, Tyumen, 625000 Russia*
*e-mail: vitaly.nowikov2017@yandex.ru
** e-mail: ksm-rabochi@rambler.ru
*** e-mail: muratows@mail.ru
**** e-mail: parahinas@tyuiu.ru

Abstract—Magnetoelastic demagnetization of steels 60G and 65G after quenching and tempering under static and dynamic mechanical stress has been studied. According to the results of the research, the magnetoelastic sensitivity to applied loads and its dependence on the steel heat treatment mode were determined. Magnetostriction and coercive force of steels 60G and 65G were measured. The connection of the magnetoelastic sensitivity of the studied steels and the level of elastic stresses with their coercive force and magnetostriction is established. A method for estimating the magnetostriction of structural steel by the magnitude of the coercive force and the level of magnetoelastic demagnetization under mechanical action on steel is proposed. The results obtained can contribute to improving the accuracy of evaluating the elastic stress in a steel structure by magnetoelastic methods.

INTRODUCTION

The magnetostriction constants of ferromagnetic steel are determined by the chemical composition and phase−crystal structure of the ferromagnet. The positive component of magnetostriction is determined by the spatial distribution of magnetic phases and its value for the same material can have a value close to zero or to a constant depending on its texture [2−5]. Therefore, magnetostriction is a magnetic parameter most structurally sensitive to mechanical stresses [6−10], to plastic [11, 12] and fatigue strain [11−15], and to the level of thermomagnetic treatment. It is included in the formula for magnetoelastic energy and determines magnetoelastic phenomena, including the magnetoelastic sensitivity of coercive force and residual magnetization to stresses [11, 16, 17] and the piezomagnetic effect of residual magnetized state [15]. Therefore, the study of magnetostriction is relevant despite the complexity of its measurement.

Similar to resistance strain gauges, the relative sensitivity of a magnetoelastic material can be characterized by the strain sensitivity coefficient [18]. The magnetoelastic properties of the material are also characterized by relative magnetoelastic sensitivity [19−21].

The use of magnetoelastic phenomena in nondestructive testing is poorly developed, since their implementation involves the ferromagnet being affected not only by magnetic field but also by external mechanical stress. In laboratory conditions, it is easy to implement for a separate steel sample not only in uniaxial
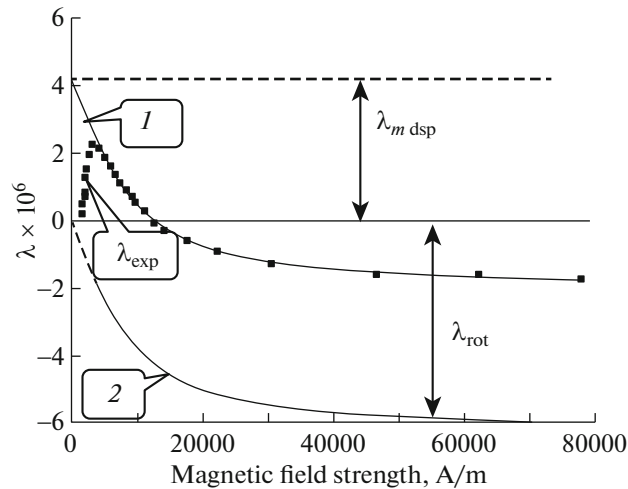
Fig. 1. Field dependence (marker ■) of magnetostriction of hardened steel 60G tempered at 700°C with the approximating Langevin function (*1*) and the curve λ_{rot} (*2*).

but also in triaxial version. Controlled loading of the structure and its elements is not always possible. However, local loading can be carried out with the help of such force-acting devices as a clamp, a jack, and a spring striker [22−24]. In this case, the intensity of the local magnetization stray magnetic field is measured and such a complex parameter as the magnetoelastic sensitivity Λ of the residual magnetized state of steel (MES) is estimated, depending mainly on its magnetic rigidity and magnetostriction,

$$\Lambda = \frac{H_0 - H_\sigma}{H_0 \sigma} = \frac{\delta H}{\sigma}, \tag{1}$$

where H_0 and H_σ are the intensities of the local magnetization stray magnetic field of steel before and after its loading and unloading, respectively, and σ is the amplitude of mechanical stresses applied to steel.

The use of the field dependence of magnetostriction for explaining magnetoelastic phenomena in low-carbon steel is not always correct, since it is the difference between two components of magnetostriction—displacement magnetostriction and rotation magnetostriction [5, 11, 25]. For example, the zero on the magnetostriction field curve (Fig. 1) only means that the displacement magnetostriction is compensated for by the rotation magnetostriction, and it is does not prove that the magnetoelastic energy in this field H is zero. The separation of iron magnetostriction into components was considered theoretically in [5]. In [11], a graphical approach was used, and the approximating Langevin function was used in the papers [25−27]

The aim of this work was to study the dependence of the magnetoelastic sensitivity (MES) of magnetoelastic demagnetization of 60G and 65G steels on the tempering temperature and on the level of elastic stresses and its relationship with the coercive force and displacement magnetostriction.

MATERIALS AND METHODS

We examined steel 60G in the form of standard samples for mechanical tests with a length of 100 mm and a diameter of the working part of 10 mm and steel 65G in the form of disks with a diameter of 75 mm and a thickness of 9.8 mm. The magnetization M_r of the studied steels was determined by the intensity of the stray magnetic field $H \sim M_r$ with a ferrosonde magnetometer and a F191 microwebermeter, and the coercive force was determined by the hysteresis loop in the fields of 140 kA/m. Magnetostriction was measured by the bridge method in the magnetic field of a solenoid on samples for mechanical tests (steel 60G) using glued strain gauges. Magnetostriction calibration was carried out on a nickel calibration block. In the course of the research, the magnetoelastic sensitivity of steel 60G to axial tension stresses and of 65G steel to local compression stresses after impact was calculated. The steel 60G samples were stretched 10−30 times on a stand based on a CD-20PU machine along the direction of their magnetization by the magnetic field of the solenoid. Samples made of steel 65G in the form of disks were magnetized by repeatedly (up to 10 times) passing current pulses through the coils of a magnetizing coil with a diam-

eter of 30 mm located on their surface. As a result, a region of local residual magnetization (LRM) was created in the samples. With the help of ferrosonde magnetic field sensors of the ICNM-2FP magnetometer, the tangential component of the intensity of the stray magnetic field H_0 LRM was determined at its maximum. Stresses of local compression of disks along the normal at the LRM center were created by means of subjecting them to a shock action, after which the intensity of the LRM stray magnetic field H_σ was measured again. The magnetoelastic sensitivity Λ of steel 65G to compression stresses σ by impact was calculated by formula (1). Shock local loading of various levels (five times), coaxial magnetization of disks made of steel 65G, and magnetic measurements were carried out in a device described in detail in [24].

RESULTS AND DISCUSSION

The field dependence of the magnetostriction $\lambda_{exp}(H)$ of steel 60G is shown in Fig. 1. According to [5, 11, 25], it is the sum of two monotone functions

$$\lambda_{exp}(H) = \lambda_{dsp}(H) + \lambda_{rot}(H), \tag{2}$$

where $\lambda_{dsp}(H)$ and $\lambda_{rot}(H)$ are proportional to the constants λ_{100} and λ_{111}, respectively.

In fields an order of magnitude stringer than the coercive force of steel 60G (200−4000 A/m), the displacement processes practically end, and the displacement magnetostriction reaches saturation and ceases to change the experimental magnetostriction curve. In this case, the dependence $\lambda_{exp}(H)$ (the curve marked with ■ in Fig. 1) will be the dependence $\lambda_{rot}(H)$ (curve 2 in Fig. 1) of the negative component of magnetostriction shifted upwards by the amount of $\lambda_{m\,dsp}$. To describe it, the Langevin function (3) was used as an approximation (curve 1 in Fig. 1) [25−27], which, as can be seen from Fig. 1, agrees well with the experiment for the following values of the constants: $C_1 = -6.2389$, $C_2 = 4.0963$, and $\alpha_1 = 0.02355$. The result of extrapolation is $\lambda_{m\,dsp} = 4.1 \times 10^{-6}$ and $\lambda_{rot} = -6.2 \times 10^{-6}$ with a deviation of 0.013,

$$\lambda = C_1 L(\alpha_1 H) + C_2,$$
$$L(x) = \coth(x) - \frac{1}{x}. \tag{3}$$

For $H = 0$, it begins with the coordinate $\lambda_{m\,dsp}$, equal to $\sim 4 \times 10^{-6}$ (see Fig. 1). The curve $\lambda_{rot}(H)$ shifted down by $\lambda_{m\,dsp}$, i.e., to the origin, will represent the magnetostriction of rotation—the negative component of magnetostriction. In this case, we exclude the contribution of displacement processes to the resulting (experimental) magnetostriction.

The positive component of the displacement magnetostriction will be expressed by the curve $\lambda_{dsp}(H) = \lambda_{exp}(H) - \lambda_{rot}(H)$ for fields providing saturation of displacement processes.

According to the results of decomposition of experimental curves $\lambda_{exp}(H)$ for steel 60G in the tempered state, four dependences were constructed sequentially (Fig. 2): the calculated value of λ_m for the largest field, the positive (peak) values λ_p of magnetostriction at maximum, the negative experimental values of magnetostriction in the maximum field of λ_s, and the negative component of magnetostriction obtained for those same fields of λ_{rot} depending on the tempering temperature of hardened steel 60G (without taking into account the demagnetizing factor of the mold).

It can be seen that the components λ_m and λ_{rot} increased in absolute value by 8 times with an increase in the steel tempering temperature. The growth rate of magnetostriction λ_m and λ_{rot} is highest in the temperature range 300−400°C. Figure 3 shows the dependence of the magnetization $M_{r\sigma}$ after applying and removing tensile stresses of 25, 65, 130, 195, and 325 MPa, and Fig. 4 shows the magnitude of the coercive force N_s of steel 60G on the tempering temperature T_{tmp}.

The magnitude of the magnetization $M_{r\sigma}$ in the entire temperature tempering range changed by (4−20) times and H_c, by 3.7 times. A characteristic peak of these quantities is observed on the curves $M_{r\sigma}(T_{tmp})$ and $H_c(T_{tmp})$ in the temperature range 450−550°C. It is associated with the release of carbides, the fragmentation of the domain structure, and the occurrence of flux-closure domains [28].
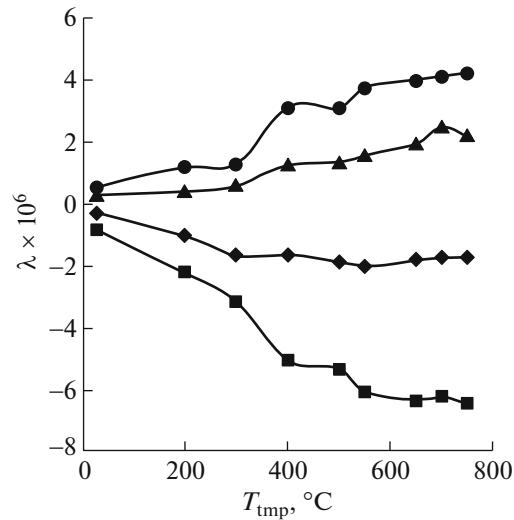
Fig. 2. Dependence of the components λ_{rot} (■), λ_s (◆), λ_p (▲), and λ_m (●) of magnetostriction of steel 60G on tempering temperature.
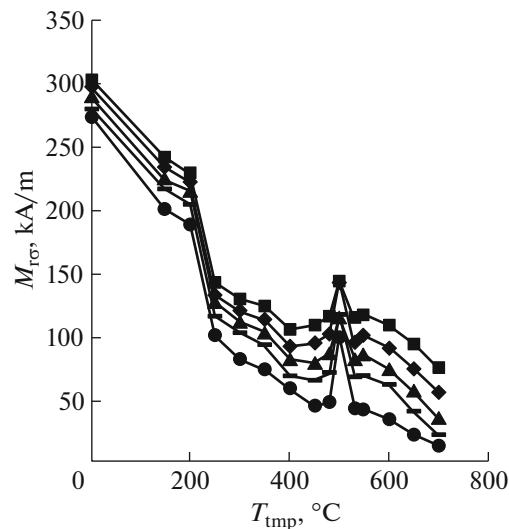

Fig. 3. Dependence of the residual magnetization $M_{r\sigma}$ of steel 60G after application−removal of tensile stresses σ: 25 (■), 65 (◆), 130 (▲), 195 (−), and 325 (●) MPa on tempering temperature T_{tmp}.

The change in the magnetoelastic sensitivity of steel 60G, determined due to the proportionality of $H \sim M_r$ by the ratio $\Lambda = (M_{r0} - M_{r\sigma})/(M_r \sigma)$, is shown in Fig. 5. It can be seen that its monotone growth is interrupted by a sharp jump down in the temperature range 450−550°C.

The magnetoelastic sensitivity increased ultimately by 7−12 times, as did the displacement magnetostriction (see Fig. 2). With the type of force action used (loading−unloading), demagnetization occurs mainly due to the processes of displacement, which determines hysteresis in steels. We proceeded from the fact that the hysteresis of rotation processes under the loads used and, accordingly, the magnetoelastic energy is small and the role of magnetostriction of rotation practically does not affect magnetoelastic demagnetization.

In practice, it was important to find out how the magnetic and magnetoelastic parameters change during the transition from a residual magnetized sample of finite dimensions to a local magnetization (LRM) created by a current pulse from a coil 30 mm in diameter on the disks with the diameter of 75 mm.
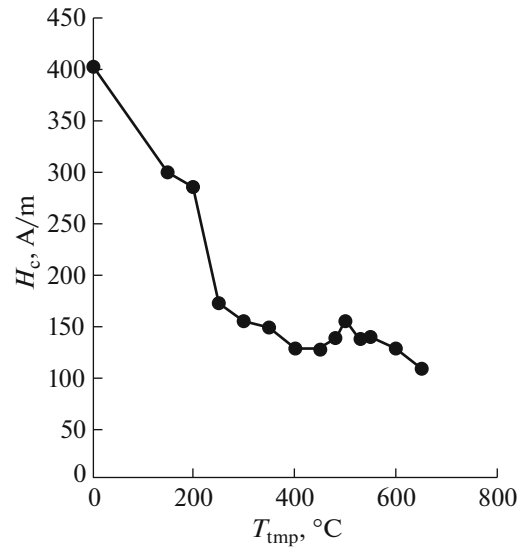
Fig. 4. Dependence of the coercive force H_c of steel 60G on tempering temperature T_{tmp}.
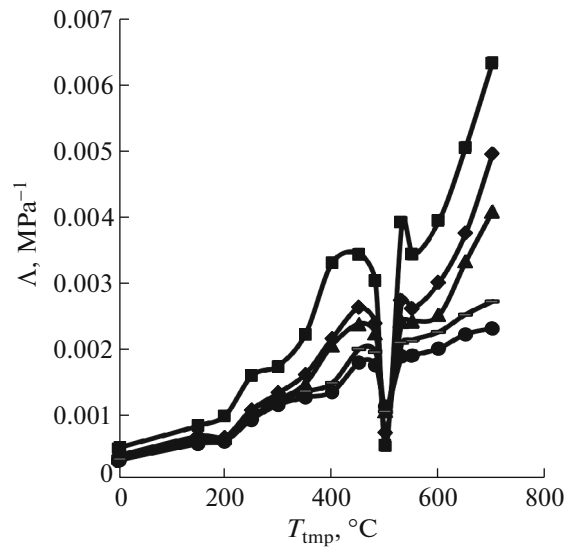

Fig. 5. Dependence of the magnetoelastic sensitivity Λ of steel 60G on tempering temperature T_{tmp} for stresses σ: 25 (■), 65 (◆), 130 (▲), 195 (−), and 325 (●) MPa generated by axial stretching.

The loading of a part of local magnetization was carried out by striking a striker with a diameter of 11 mm on the surface of steel. Figures 6 and 7 show the dependence of the local magnetization stray magnetic field strength H_σ of steel 65G after exposure to shock stresses of 12, 25, 38, 51, and 76 MPa and the magnitude of its coercive force H_c on the tempering temperature, respectively. It can be seen that the coercive force of hardened steel 65G is 1.6 times higher than that of steel 60G, and the field strength H_σ is 4–4.2 times stronger.

The magnitude of the intensity of the LRM stray magnetic field H_σ in the entire tempering temperature range changed by 10–11 times and N_c, by 2.1 times. A pronounced peak of these quantities associated with the release of carbides, the fragmentation of the domain structure, and the occurrence of flux-closure domains, is also observed on the curves $H_\sigma(T_{tmp})$ and $H_c(T_{tmp})$ in the temperature range 650–775°C. The magnetoelastic sensitivity of steel 65G to shock stresses in the temperature range up to 200°C does not change and then starts to increases dramatically up to 650°C. In general, the MES increased ultimately by 7.6 times (Fig. 8).
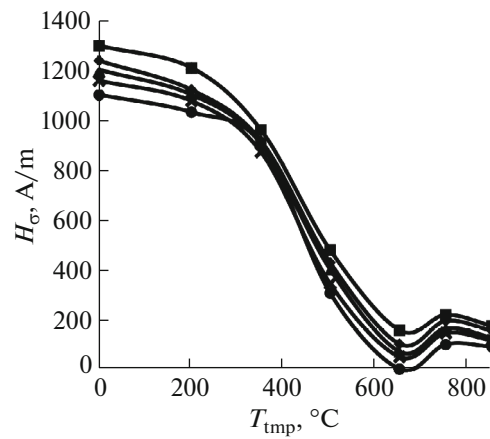
Fig. 6. Dependence of the LRM stray magnetic field strength H_σ of a steel 65G sample in the form of a disk after the application of shock stresses σ: 12 (■), 25 (◆), 38 (▲), 51 (×), and 76 (●) MPa on tempering temperature T_{tmp}.
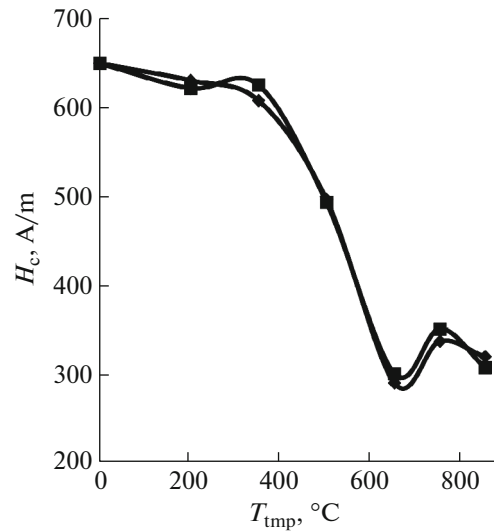

Fig. 7. Dependence of the coercive force N_c of steel 65G measured in the longitudinal (◆) and transverse (■) directions on tempering temperature T_{tmp}.

A comparison of the magnetic and magnetoelastic properties of standard samples made of steel 60G for mechanical testing (practically, a cylinder) magnetized entirely along the axis in the magnetic field of a solenoid subjected to uniaxial (homogeneous) stretching and samples made of steel 65G in the form of disks magnetized locally by a magnetic field pulse of the attached coil normally to the surface and loaded with a compressive shock shows that the studied phenomena are not only qualitatively similar (the proportionality of the coercive force H_c and the local magnetization stray magnetic field intensity H) but also demonstrate close values of the magnetoelastic sensitivity Λ to various types of loading. It is noteworthy that the local magnetization of steel 65G is induced on the area of a circle with a diameter of 30 mm, the shock load is applied directly to a part of the magnetized area (the diameter of the striker is 11 mm), but the change in the magnetic field strength of the local magnetization of steel 65G is virtually the same as that of the entire cylindrical sample of steel 60G when it is loaded with axial tension, i.e., a shock wave running through the sample performs its magnetoelastic demagnetization. This gives hope for a possible technical application of the local loading method for studying magnetoelastic phenomena in steels. Thus, the variation in the readings for repeated measurements of the field strength H_σ after shock loading and the error in determining the magnetoelastic sensitivity in this way was 5−9%.

The relationship between the magnetoelastic sensitivity Λ, the coercive force H_c, and the corresponding magnetostriction λ (λ_m or λ_p) of steel can be obtained from the hyperbolic [11] and exponential [24, 28] laws of magnetoelastic demagnetization, respectively.

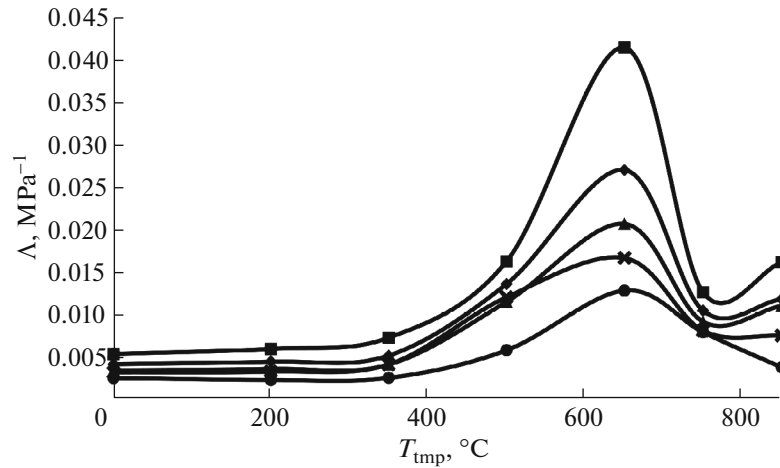**Fig. 8.** Dependence of the magnetoelastic sensitivity Λ of a steel 65G disk sample on tempering temperature T_{tmp} under various shock stresses: 12 (■), 25 (◆), 39 (▲), 51 (×), and 76 (●) MPa.
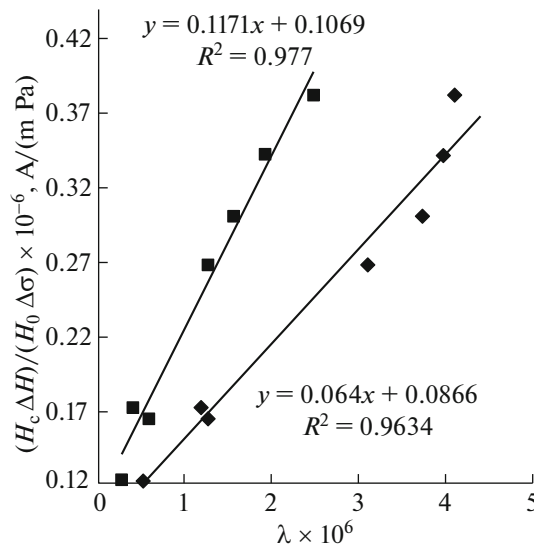

Fig. 9. Dependence of the product of the magnetoelastic sensitivity Λ of steel 60G and its coercive force H_c on the magnetostriction λ_m (◆) and λ_p (■), respectively.

With the hyperbolic approximation [11],

$$\beta_i \frac{H_c \Delta H}{H_0 H_\sigma \Delta \sigma} = \Lambda \frac{H_c}{H_\sigma} = \lambda. \tag{4}$$

With the exponential approximation [24, 28],

$$\gamma_i \frac{H_c \Delta H}{H_0 \Delta \sigma} = \Lambda H_c = \lambda, \tag{5}$$

where Λ is the magnetoelastic sensitivity of the residually magnetized sample (sample element) (1), and β_i and γ_i are the proportionality coefficients.

Graphically, this relationship for steel 60G is shown in Figs. 9 and 10. It can be seen that the peak value of magnetostriction λ_p correlates better with the proposed regression equations than λ_m. According to the results shown in Figs. 9 and 10, using the proposed relationship of coercive force and magnetoelastic sen-
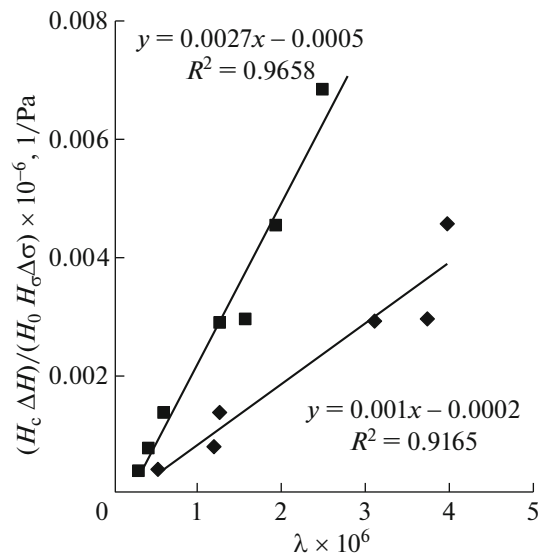
Fig. 10. Dependence of the ratio of the product of the magnetoelastic sensitivity Λ of steel 60G and its coercive force H_c to the stray magnetic field strength H_σ after loading–unloading on the magnetostriction λ_m (◆) and λ_p (■), respectively.

sitivity, the magnetostriction of λ_m and λ_p can be estimated using the magnetoelastic method with an error of 4 to 15%.

CONCLUSIONS

1. The experimental field dependence of magnetostriction of tempered steel 60G is divided into a positive component, due to the processes of displacement of interdomain boundaries, and a negative component, associated with the processes of rotation.

2. The relationship of displacement magnetostriction and coercive force with the sensitivity of steels 60G and 65G to elastic stresses during magnetoelastic demagnetization has been established. It is suggested that it is realized mainly by the processes of irreversible displacement of interdomain boundaries.

3. A method of indirect estimation of the magnetostriction of structural steels by the magnitude of magnetoelastic demagnetization under mechanical action on steel and coercive force is proposed. The results obtained can contribute to improving the accuracy of evaluating elastic stresses in a steel structure by magnetoelastic methods.

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