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ELECTRICAL AND MAGNETIC PROPERTIES

Magnetoelastic Demagnetization of Steel under Cyclic Loading

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Abstract—Magnetoelastic demagnetization of steel samples under cyclic tensile loads has been analyzed. It has been established that values of residual magnetization that correspond to peak loads are characterized by the power-law dependence on the number of loading cycles. In some cases, in the region of high loads, the qualitative transition to exponential dependence has been observed. Coefficients of the power-law approximation of peak magnetization depend on the value of amplitude load and have specific characteristics in the vicinity of characteristic loads. The ratios of approximated slide load coefficients depending on the load are common for the three considered samples, and there is an outburst in the vicinity of the fatigue limit, which can be used as the basis for developing the rapid nondestructive method for determination of this limit.

Keywords: magnetoelastic demagnetization, piezomagnetic effect, power-law relaxation, cyclic loading, fatigue limit

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INTRODUCTION

The determination of the fatigue limit σ_R of steels [1–3] is time- and labor-consuming because the accumulation of fatigue defects and their manifestation in the form of the failure of a sample requires a large number of cyclic loadings (~10^6–10^7) and numerous samples. The obtained value of σ_R reflects the properties of the considered group of samples, since the lifetime of an individual sample (number of cycles to failure), other conditions being equal, can differ by many times. This stipulates a certain reserve of strength during the design stage, which is a compromise between the reliability and low cost of the product.

The accumulation of fatigue defects becomes noticeable at loads higher than σ_R. The detection of their nucleation with a gradual increase in the amplitude of low cyclic loadings would enable the detection of σ_R and, perhaps, without a significant violation of product operability, that is, by a nondestructive procedure. In addition, monitoring of degradation degree would permit sufficiently reliable forecasting of remaining operation lifetime of product. Estimation of fatigue limit of each individual product is quite obvious for rod well pumps, since failure of their elements results both in direct and indirect losses.

The accumulation of fatigue defects is time-consuming; hence, the physical parameters (electric, acoustic, and so on), which could reflect the degradation of the material prior to the occurrence of microcracks, vary slightly. The periodic events of relief of accumulated microstresses in metal reset these parameters to the initial state, which is stipulated by the independent contribution of the state of individual local segments of material into a cumulative parameter, e.g., electric resistance.

One of the approaches to solving this problem is to analyze the variations in the residual magnetization during cyclic loading without magnetic bias field. The selection is based on the fact that the domain structure of ferromagnetic is the system of interacting elements. Variations in the state of the individual domain, caused by microplastic deformation, as a consequence of the magnetic interactions would lead to the inevitable variations in the state of adjacent domains, which in turn influence the subsequent domains. Therefore, the information of state variations in each element of the systems will be transferred to surrounding elements, and this system will be characterized by memory.

The researchers in [4–8] analyze such parameters as coercive force, magnetic hysteresis loop, intensity of scattering field, and others. We studied parameters of the intensity relaxation of the magnetic scattering field H_s of residual magnetization of steel with an increase in the number of loading cycles.

During the loading of the magnetized steel sample, as a consequence of variations in the magnetoelastic energy, the energy balance of domains is modified, which in turn alters the domain structure and demagnetizes the steel. Further loadings and unloadings successively bring the domain system (interdomain boundaries) closer to a certain steady-energy state at preset loading amplitude. When load exceeds fatigue

Table 1. Properties of samples

<table>
<tr><td colspan="20">Chemical composition, %</td></tr>
<tr><td colspan="4">C</td><td colspan="4">Si</td><td colspan="4">Mn</td><td colspan="4">Cr</td><td colspan="4">Ni</td></tr>
<tr><td colspan="4">0.13</td><td colspan="4">0.21</td><td colspan="4">0.64</td><td colspan="4">0.075</td><td colspan="4">0,08</td></tr>
<tr><td colspan="4">Al</td><td colspan="4">Cu</td><td colspan="4">V</td><td colspan="4">S</td><td colspan="4">P</td></tr>
<tr><td colspan="4">0.025</td><td colspan="4">0.188</td><td colspan="4">0.018</td><td colspan="4">0.015</td><td colspan="4">0.024</td></tr>
<tr><td colspan="20">Mechanical properties (averaged)</td></tr>
<tr><td colspan="5">HRB</td><td colspan="5">KCV, J/cm^2</td><td colspan="5">$\sigma_{0.2}$, MPa</td><td colspan="5">σ_u, MPa</td></tr>
<tr><td colspan="5">89.1</td><td colspan="5">143.4</td><td colspan="5">597</td><td colspan="5">627</td></tr>
<tr><td colspan="20">Normalized state, grain rating: 7–8 according to GOST Russian State Standard 5639-82</td></tr>
</table>

limit, which leads to the occurrence of defects of crystalline lattice, it is possible to expect the modification of either the relaxation pattern of magnetization or its parameters. Hence, the detection of the initiation of this modification can indicate that the fatigue limit is being approached.

An analysis of residual magnetization was selected based on the following considerations. Without an external magnetic bias, the mechanic load is the only source of influence on the structure of the magnetic domains (their topology). In the course of cyclic loading, the information about the occurring slight modifications of material is accumulated. While recording, e.g., the magnetic hysteresis loop or coercive force after each experimental series, noticeable modifications can only be expected after a significant number of loadings or changes of the loading amplitude [4], since the external field erases the information accumulated by the structure of magnetic domains.

EXPERIMENTAL

Magnetoelastic tests were performed on three samples of steel produced in Canada and intended for the fabrication of the well pump rod. Table 1 summarizes the information about chemical composition and mechanical properties of preliminary tested samples. Figure 1 illustrates the experimental assembly on the basis of an IR-50 tension machine. Sample *1* preliminary magnetized to saturation, was installed in the tension machine using nonmagnetic supports *2*. Helmholtz coils *3* compensated for the vertical constituent of Earth field. The ferroprobe *4* of magnetic meter *5* measured the horizontal constituent of the magnetic field of sample residual magnetization, H_s.

It has been demonstrated preliminarily that H_s is proportional to the magnetization M of the sample. Thus, it is possible to estimate the variations in the magnetization of the sample based on the H_s measurements. Cyclic zero-to-tension ($R_\sigma = 0$) tests were performed with successive increases in amplitude by ~50 MPa after each 100 cycles. During cycling, H_s was synchronously recorded. The intensity of the magnetic scattering field was measured by an IKNM-2FP device. The samples were magnetized before each series of 100 loadings. They were dismounted from the assembly and placed into a magnetizing coil.

In order to estimate the influence of the loading rate, preliminary tests were performed at various loading rates in the range of 4–15 mm/min, which demonstrated the insensibility of magnetization to this factor. Thus, in order to save time, the loading rate was varied so that an experimental series be performed in 10–15 min. The data were recorded every 0.1 second.

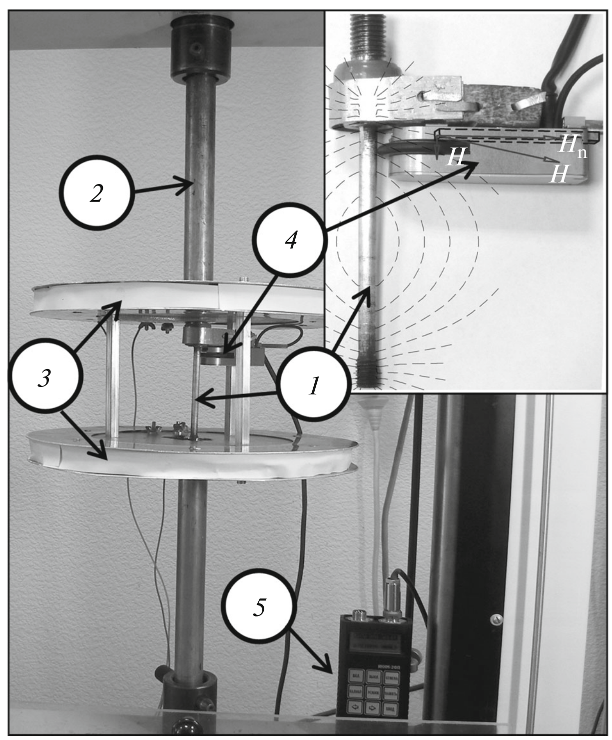

Fig. 1. Experimental assembly: (*1*) sample; (*2*) nonmagnetic holder; (*3*) Helmholtz coils; (*4*) ferroprobe; (*5*) magnetometer.

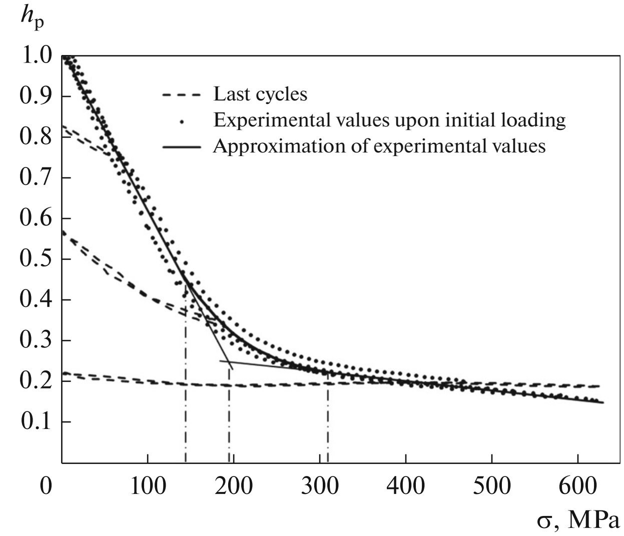

Fig. 2. Magnetoelastic demagnetization curves of residually magnetized sample no. 1.

RESULTS AND DISCUSSION

Demagnetization Pattern upon Initial Loading

Similar to [7], for the considered steel the curve of magnetoelastic variation $H_s(\sigma)$ in Fig. 2 was analyzed in fractions of initial intensity of the magnetic field of residual magnetization, H_r, where $h_s = H_s/H_r$. The use of the relative variable h_s was dictated by the need to minimize the positioning error, which nevertheless manifested upon the reinstallation of samples after magnetization.

On the curve of irreversible demagnetization after initial loading, as in [7], it is possible to observe two linear segments, the first of which is mainly stipulated by the mechanism of motion of interdomain boundaries, while the second is caused by the revolution of the magnetization vectors. It is possible to highlight three characteristic values of mechanic stresses, i.e., 145 MPa at the end of the first linear segment, 310 MPa at the start of the second linear segment, and 195 MPa at their intersection. Dashed lines illustrates the pattern of the last cycles of some experimental series, with the negative piezomagnetic effect to observe ($dh_s/d\sigma < 0$), its value decreases with an increase in the amplitude of loading. It is interesting to note that, in the last cycle, at a loading amplitude of 625 MPa, a segment with a positive piezomagnetic effect is observed in the interval of 200–450 MPa, which subsequently becomes negative again. In addition, magnetization at a maximum load of this cycle is higher than during the first cycle, which was observed at high amplitude loads (>500 MPa). Test results of other samples also demonstrated a similar pattern of the curve of magnetoelastic demagnetization. The characteristic stresses were as follows: for sample No. 2, stresses were 120, 175, and 310 MPa and, for sample No. 3, they were 125, 162, and 245 MPa. It should be mentioned that the considered values characterize averaged lines of approximation obtained based on a combination of several experimental series, including those at loads close to the yield point. The scatter of each of these values was about 30–50 MPa.

Relaxation Pattern of Peak Values of Magnetization during Cyclic Loading

The values of stresses that characterize transitions between the mechanisms of demagnetization (Fig. 2) are stipulated by the magnetic properties of magnetic material and probably related to the fatigue limit [7]. Fatigue failure is a multifactor phenomenon, and it is necessary to take into account that it is a combination of several concurrent processes [1–3, 9] that are intensified at different stresses and compete with each other. These processes can variously influence the pattern of individual branches of the magnetoelastic demagnetization curve (Fig. 2) and can go undetected due to negligible influence. The accumulation of the influence of these processes on the magnetoelastic response of magnetic material (its relaxation) to the measured values can permit one to detect their characteristic initial stresses. In other words, simultaneous analysis of the overall magnetoelastic cyclogram is required. With this goal, the pattern of variations in h_s is analyzed as a function of the increase in the number of loading cycle N. Figure 3 illustrates the pattern of the first 25 cycles of h_s variations. After the first loading, there is a significant irreversible decrease in the field intensity of residual magnetization and, after unloading, its quasi-reversible growth occurs. Subsequent cyclic loadings lead to a smooth decrease in residual magnetization.

An analysis of the obtained data demonstrated that, in most cases, the h_s peak values that correspond to the amplitude load or its absence are poorly approximated by an exponential dependence and can be well approximated by power functions as follows:

$$h_{s\sigma_{\max}} = h_{\sigma_{\max}} + \Delta h_{\sigma_{\max}} N^{-\alpha_{\sigma_{\max}}}; \quad h_{s\sigma_{\min}} = h_{\sigma_{\min}} + \Delta h_{\sigma_{\min}} N^{-\alpha_{\sigma_{\min}}}. \tag{1}$$

Here $h_{\sigma_{\max}}$ and $h_{\sigma_{\min}}$ reflect the steady state of the magnetic material with and without the load at $N \to \infty$; $\Delta h_{\sigma_{\max}}$, $\Delta h_{\sigma_{\min}}$ each is the slide value. The power indices $\alpha_{\sigma_{\max}}$, $\alpha_{\sigma_{\min}}$ are responsible for the rapidity of irreversible demagnetization with increase in cycle number. The indices $\sigma_{\max}$ and $\sigma_{\min}$ correspond to the amplitude load in an experimental series and to the unloaded state, respectively.

The high extent of the correlation with power-law regularity was observed for peak values of magnetization without load ($h_{s\sigma_{\min}}$), where the coefficient of the approximation validity averaged over all experimental

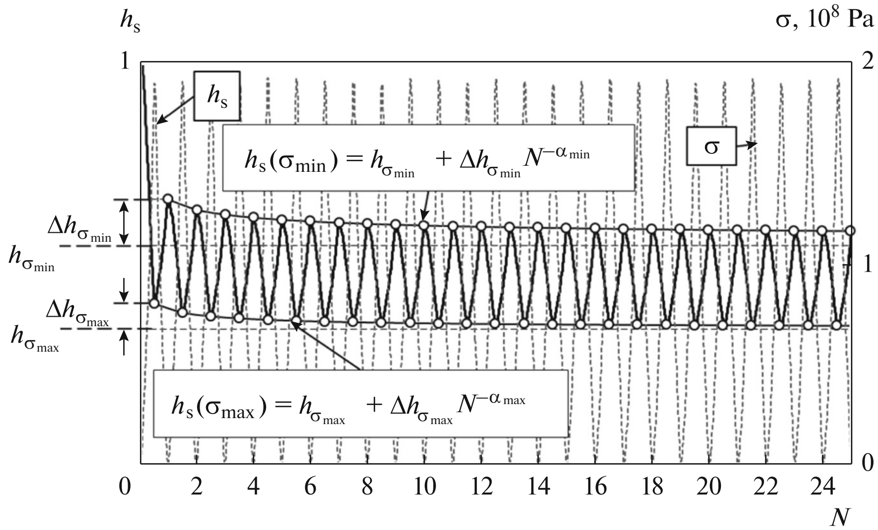

Fig. 3. Magnetoelastic cyclogram of sample no. 1 at a loading amplitude of 190 MPa.

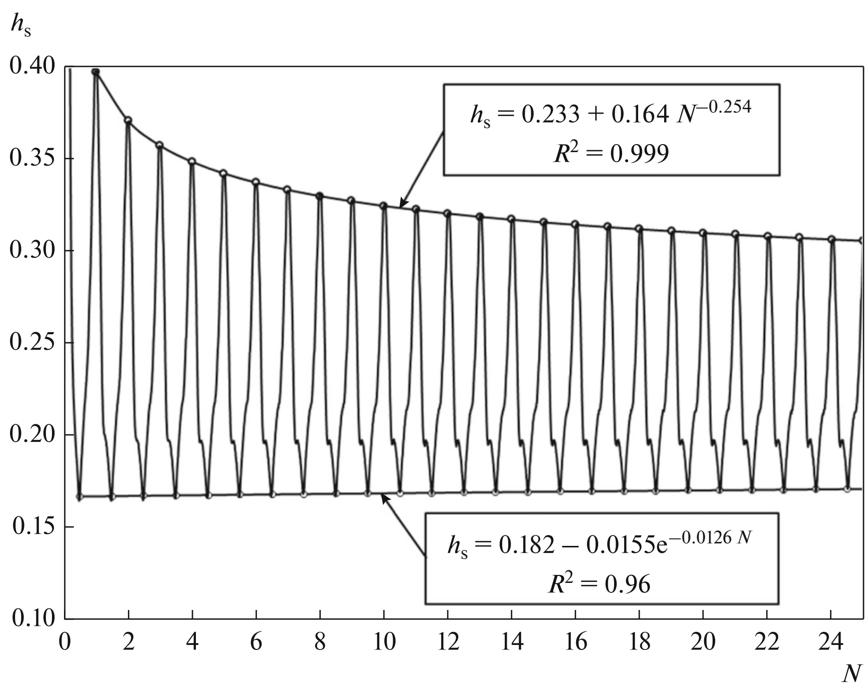

Fig. 4. Magnetoelastic cyclogram of sample no. 1 at loading amplitude of 575 MPa.

series was $R^2 = 0.99$. The power-law pattern of relaxation was also observed on steels of grades 30Kh13, 15Kh2GMF, 40Kh, and 40KhGM quenched and tempered at various temperatures, so it is possible to speak about the universality of the observed property. An analysis of works by various researchers, e.g. [12, 20], has revealed that this property can be indicative of non-Markov processes, that is, systems with memory as well as fractal systems.

For high load amplitudes, a slight increase in $h_{\sigma_{max}}$ with an increase in the number of cycles is observed (Fig. 4), which agrees with the above mentioned discussion, Fig. 2. Under these loads the approximation of $h_{\sigma_{max}}(N)$ by a power-law function results in negative values of power index α in Eq. (1). In this case, the dependence is better described by the exponent and it is possible to discuss qualitative variations in the behavior of the magnetic material under high loads.

It should be mentioned that the segment in Fig. 2 with the piezomagnetic effect manifests in the form of saw-teeth in Fig. 4 at about $h_p \approx 0.2$. Here, this tooth is absent during the initial loading cycles, but gradually

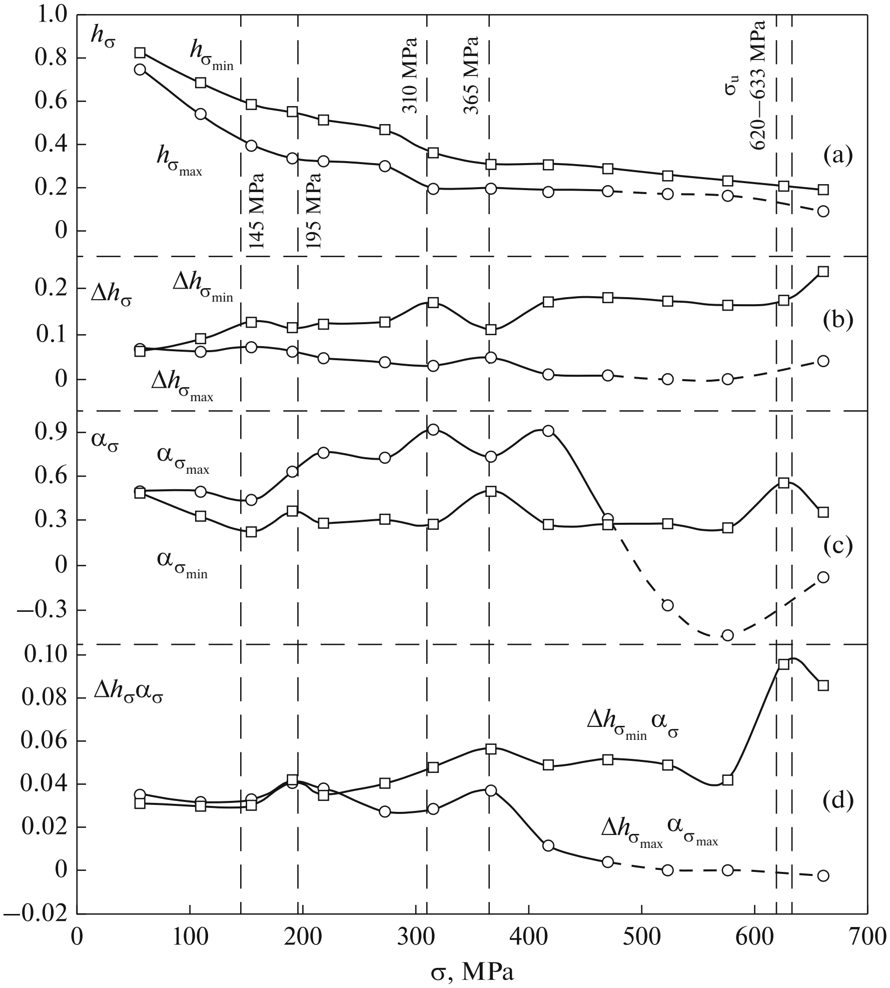

Fig. 5. Power-law approximation of peak values of magnetoelastic cyclogram of sample no. 1 as a function of loading amplitude.

appears and becomes more expressed. The occurrence of segments with a positive piezoelectric effect was observed at loading amplitudes higher than 250–300 MPa. From the point of view of searching for signs of the fatigue limit, there is interest in not the mere existence of this segment, but rather its cycle-to-cycle manifestation.

Approximation parameters $h_{\sigma_{max}}$, $h_{\sigma_{min}}$, $\Delta h_{\sigma_{max}}$, $\Delta h_{\sigma_{min}}$, $\alpha_{\sigma_{max}}$, $\alpha_{\sigma_{min}}$ as a function of loading amplitude σ are described by complex pattern. These functions for the considered samples are illustrated in Figs. 5–7. Dashed lines highlight segments of poor correlation of $h_{s\sigma_{max}}$ with the power-law dependence. Various outbursts up and down are observed and, at first sight, they have nothing in common. It can be assumed that these variations reflect the stages of various processes characteristic of the fatigue degradation of metal [9–11] individual for each sample and can identify the initiation of these processes. For instance, it can be seen that for the first sample (Fig. 5) at 145, 195, 310, and 365 MPa, synchronous curves are observed. Similarly, for sample nos. 2 and 3, synchronous bending of diagrams can be observed in the vicinity of loads characteristic of the first irreversible branches of magnetoelastic demagnetization.

The slide values $\Delta h_{\sigma_{max}}$, $\Delta h_{\sigma_{min}}$ and power indices $\alpha_{\sigma_{max}}$, $\alpha_{\sigma_{min}}$ in the form of their product $\Delta h_\sigma \alpha_\sigma$ reflect the slide rate of peak values h_s with an increase in the numbers of the cycle as follows:

$$\frac{dh_{s\sigma_{max}}}{dN} = -\Delta h_{\sigma_{max}} \alpha_{\sigma_{max}} N^{-(\alpha_{\sigma_{max}}+1)};$$
$$\frac{dh_{s\sigma_{min}}}{dN} = -\Delta h_{\sigma_{min}} \alpha_{\sigma_{min}} N^{-(\alpha_{\sigma_{min}}+1)}. \quad (2)$$

Figures 5–7 (diagrams *d*) illustrate $\Delta h_\sigma \alpha_\sigma$ as a function of the loading amplitude. At first, for all samples, curves $\Delta h_{\sigma_{max}} \alpha_{\sigma_{max}}$ and $\Delta h_{\sigma_{min}} \alpha_{\sigma_{min}}$ are actually the same, but then they have a maximum, after which, at 50 MPa, they fall apart.

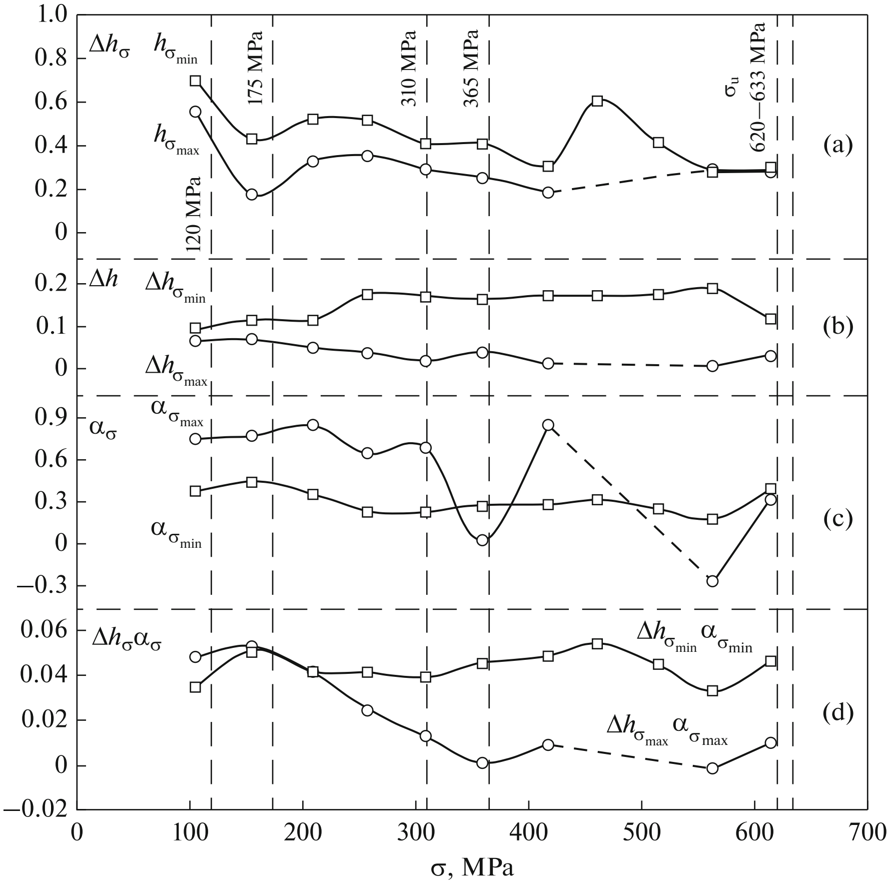

Fig. 6. Power-law approximation of peak values of magnetoelastic cyclogram of sample no. 2 as a function of loading amplitude.

Following elementary thermodynamic concepts it is possible to state that the slide parameters $\Delta h_{\sigma_{\min}}$ and $\Delta h_{\sigma_{\max}}$ are related to variations in the entropy of magnetic material by the time of established equilibrium ($N \to \infty$). Interest is attracted to the ratio $\delta h = \Delta h_{\sigma_{\min}} / \Delta h_{\sigma_{\max}}$, and its dependence on the loading amplitude is illustrated in Fig. 8. The variable δh can be interpreted as the comparison parameter of transition of magnetic material to an equilibrium state with and without the load. The activation of irreversible fatigue degradation would lead to an additional increase in entropy and, hence, variations in the balance of these processes.

It can be seen in the figure that at first the parameter δh has nearly equal values for the three samples and increases linearly. A local maximum is observed in the vicinity of 310 MPa. Then, for samples 1 and 2, a new increase in the parameter δh is observed (shown by a dotted line in the region of poor correlation), then it drops by the moment of its destruction. It is interesting to note that the drop after the first maximum and a subsequent second one takes place up to approximately the level of the dotted line; this line extrapolates the initial linear segment to a range of high loads. Let us assume that this straight segment reflects the pattern of magnetoelastic response without micro- and macroplastic deformations. Then, the segments of sharp increase in the parameter δh are probably related to the development of plastic deformations and the occurrence and development of oriented microstresses [21].

According to the aforementioned hypothesis, the load range of 250–370 MPa, which includes a local maximum (Fig. 8), is probably related to the fatigue limit of the material. Its empirical interrelation with the yield point and ultimate strength is given elsewhere [22], using this interrelation the range 200–400 MPa was estimated. Of course, this coincidence cannot be an exact confirmation of the expressed hypothesis, since the tests were only performed for one grade of steel. Thus, studies should be carried out for a series of various materials. We believe that this concept and procedure are useful.

In addition to the properties of the material (chemical composition, structure and phase state), the state of the product surface is a significant factor in the fatigue limit [1–3], and this surface contains stress concentrators (surface roughness) in addition to the negative impact of ambient environment. In the scope

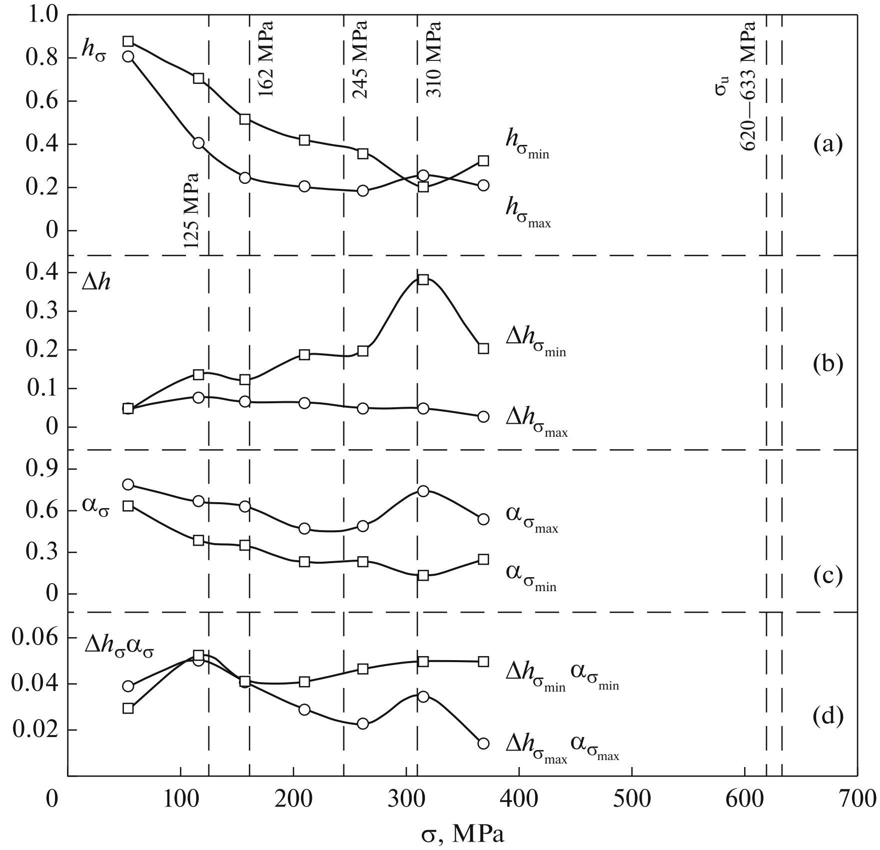

Fig. 7. Power-law approximation of peak values of magnetoelastic cyclogram of sample no. 3 as a function of loading amplitude.

of this work, due to the small number of testing cycles and the unavailability of aggressive mediums, the development of a significant amount of microdefects on the surfaces of samples compared with their core is highly improbable. Thus, the influence of surface state on the magnetoelastic signal is insignificant. Then, the stress range 250–370 MPa probably reflects the fatigue properties of the material itself.

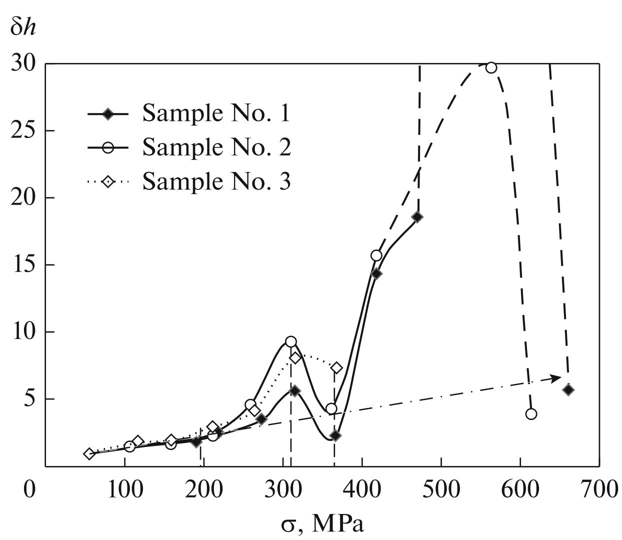

Fig. 8. Dependence of parameter δh on loading amplitude as a function for three samples.

CONCLUSIONS

According to the results of magnetoelastic cyclic tests on steel samples, the property was detected in which variations in the peak residual magnetization with an increase in the loading cycles is governed by power-law dependence. At high loads, qualitative transition to exponent dependence of magnetization is observed corresponding to amplitude load as a function of cycle number.

Coefficients of the power-law approximation as a function of the amplitude of mechanical stresses are characterized by complex pattern. In the vicinity of loads characteristic of the transition from the displacement of domain boundaries to the revolution-specific behavior, the coefficient of approximation was observed. Of particular interest is the behavior of the proposed parameter δ which has an extreme value in the vicinity of the estimated fatigue limit. This will probably permit the development of a rapid procedure for estimating the fatigue limit of ferromagnetic materials.

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