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Inversion of the piezomagnetic effect of the residual magnetized state of steel 30Kh13 during low-cycle tests

© K.R. Muratov, V.F. Novikov, R.A. Sokolov

Tyumen Industrial University, Tyumen, Russia
E-mail: muratows@mail.ru

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The results of magnetoelastic tests of hardened and tempered samples of high-chromium 30Kh13 steel, which after magnetization were subjected to low-cycle stretching, are presented. The tests were repeated with a sequential increase in the load amplitude. Stretching on the first cycle led to irreversible demagnetization of the samples. As the number of cycles increases, a quasi-reversible change in magnetization is established, called the piezomagnetic effect of residual magnetization. High sensitivity of specified effect to fatigue loads is established, active change of its sign occurs in vicinity of endurance limit.

Keywords: 30Kh13 steel (AISI 420), piezomagnetic effect, residual magnetization, cyclic tests, magnetoelastic demagnetization.

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Magnetic, electromagnetic and magnetoelastic methods have a high structural sensitivity. Therefore, they are widely used for non-destructive testing [1,2]. Recently, there has been increasing interest in the development of magnetic non-destructive testing methods for the fatigue characteristics of steels [3,4], in particular the magnetoelastic method [5,6].

The present work is devoted to the investigation of the magnetoelastic phenomena under low cycle stresses and the search for possibilities of using the magnetoelastic effect to determine the fatigue properties and the endurance life of steels [5]. 30Kh13 steel (analogue of AISI 420) was used as the material for the research. It has high strength, corrosion resistance, relatively high magnetostriction and medium magnetic stiffness [7,8].

The sample, magnetized to saturation, under cyclic loading, experiences partial magnetoelastic demagnetization which, after 10−30 cycles, acquires an established magnetoelastic quasi-reversible character, i.e. the so-called piezomagnetic residual magnetized state effect (PMR) [9–11] is established.

The test samples were 100 mm long rods with M8 threads at the ends. The working part was 80 mm long, 6 mm in diameter. Quenching from 1030−1050°C in oil and tempering at temperatures from 150 to 700°C for one hour were performed.

The experimental installation and the experiment technique are described in [5]. The first series of tests consisted of magnetization to saturation, cyclic tensile loading with an amplitude of about $\sigma_A = 150$ MPa and synchronous recording of magnetograms. Subsequent series were conducted with a load increase of approximately 50 MPa.

In the 200−500°C tempering temperature range, a positive piezoeffect is observed, which tends to decrease with increasing tempering temperature. From a tempering temperature of 530°C at a load of 630 MPa, the sign of the piezoeffect changes to negative at the 24th load cycle. For a temperature of 550°C, this is already observed at 210 MPa at cycle 4. For temperatures of 600, 650 and 700°C, the piezoeffect changes sign at 215 (cycle 11), 366 (cycle 23) and 415 MPa (cycle 13), respectively. An example of magnetoelastic cyclograms is shown in Fig. 1.

The most interesting case here is the tempering temperature 600°C, where the piezomagnetic effect is complex. Therefore, to study it in detail, two similar samples were made and repeated fifty-cycle tests were carried out. Tensile strength $\sigma_B = 850-900$ MPa [12], yield strength $\sigma_{0.2} = 710$ MPa [12], tensile strength $\sigma_{-1} = 495$ MPa [13]. The load of the first test series was 35 MPa, further increases were made by 35 MPa. Before and after the fifty-cycle tests, the magnetization was measured by removing the sample from the coil connected to F192 microwebermeter. The onset of plastic elongation of the samples was recorded at 672 MPa (sample 1) and 572 MPa (sample 2).

Figure 2 shows the diagrams of the first (*a*) and last (fiftieth) (*b*) load cycles for different amplitudes. The branch of the diagram (Fig. 2, *a*) with falling load shows a positive slope. For amplitude loads of 565 MPa (Fig. 2, *a*) and above, a change in demagnetization pattern is observed under loading compared to lower amplitudes, indicating the presence of irreversible changes in the material. In the first exposure cycle, the residual magnetization is irreversibly reset (40−90%) and further demagnetization takes place against the PMR background.

The magnetoelastic loops on subsequent cycles ($N = 2-50$) are characterized by a positive piezomagnetic effect (Fig. 2, *b*) up to and including the 493 MPa series. From 536 MPa onwards, the second and subsequent loops

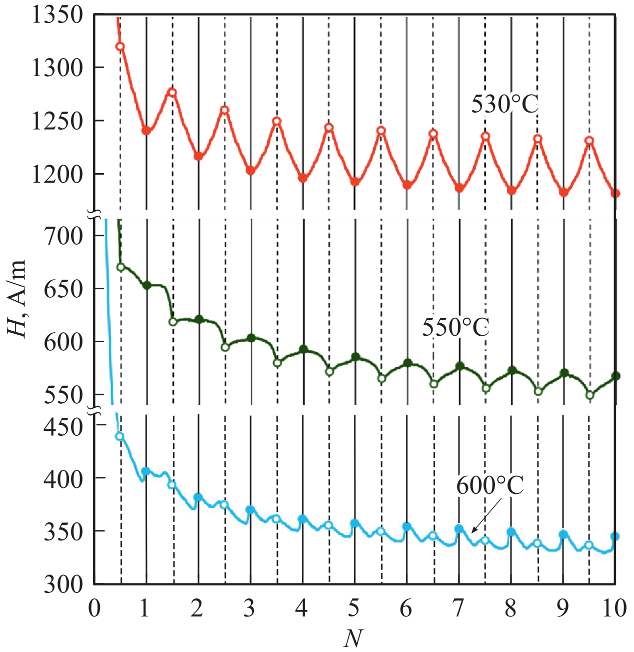

Figure 1. Character of the change in the magnetic field strength of the residual magnetization with increasing loading cycle number with 265 MPa amplitude for 30Kh13 steel samples after quenching and tempering at 530, 550 and 600°C. The solid vertical lines correspond to zero load, the dotted — amplitude load.

become increasingly complex with increasing cycle number: in the low load region, a negative piezoeffect is observed, changing to a positive one with increasing load within the cycle (Fig. 2, *b*).

In order to quantitatively describe the transformation of the piezoeffect of the last cycles with increasing load, the magnetoelastic sensitivity of the piezoeffect $\Lambda = \Delta M/\Delta\sigma$ in the magnetoelastic loop sections of the 50th cycle is determined. Near $\sigma = 0$, the sensitivity Λ_0 was determined by a segment drawn through the self-intersection point of the loop (Fig. 2, *b*). Near the amplitude load, the sensitivity Λ_σ was found from the falling load section. The cumulative magnetoelastic sensitivity was determined from the loop spread: $\Lambda_\Sigma = (M_{\sigma A} - M_0)/\sigma_A$, where M_0 and $M_{\sigma A}$ — magnetization values at zero and amplitude load, respectively (Fig. 2, *b*).

Figure 3 shows the pattern of change in Λ_0, Λ_σ and Λ_Σ with increasing σ_A for the two samples. In 40–250 MPa range, these values vary almost equally, which is due to the practical linearity of the magnetoelastic loops. A further increase in load causes them to curve, which is reflected in the divergence of the curves $\Lambda_0(\sigma_A)$, $\Lambda_\sigma(\sigma_A)$ and $\Lambda_\Sigma(\sigma_A)$. Starting at loads of the order of 450 MPa one can see the beginning of an intense decay of the curve $\Lambda_0(\sigma_A)$ and a transition to negative values of $\Lambda_0(\sigma_A)$. This causes inversion of the magnetoelastic signal, i.e. the piezoeffect becomes negative. Note that such sharp changes are observed in the vicinity of the endurance limit ($\sigma_{-1} = 495$ MPa [13]).

With a further increase in load amplitude, an inversion of Λ_σ sign is also observed (at 520–550 MPa). In this case, Λ_Σ remains positive up to loads close to the yield strength, which is due to the presence of positive piezoeffect regions in the magnetoelastic loops (Fig. 2, *b*). Near $\sigma_{0.2}$, the dependences $\Lambda_0(\sigma_A)$ and $\Lambda_\sigma(\sigma_A)$ show an extremum (Fig. 3). This is probably due to the release of the internal stresses accumulated by this point through intense plastic deformations.

It is noteworthy (Fig. 2, *b*, inset with intermediate loops) that with increasing cycle number within a test series, the magnetoelastic sensitivity of Λ_σ hardly does not change, whereas Λ_0 changes significantly, i.e. this parameter is most sensitive to the cyclic operating time.

According to the known thermodynamic relation [14, p. 40]

$$\left(\frac{\partial M}{\partial \sigma}\right)_H = \frac{1}{l_0}\left(\frac{\partial l}{\partial H}\right)_\sigma \quad (1)$$

for materials with positive magnetostriction ($\partial l/\partial H > 0$, where ∂l — elongation along the strength of H; l_0 — initial linear dimension), the magnetization change ∂M under tension ($\partial\sigma > 0$) must be positive, and under compression ($\partial\sigma < 0$) — negative. The negative PMR of 30Kh13 steel, which has a positive magnetostriction [15], seems at first glance to contradict relation (1). In works [10,15], the negative piezoeffect of the material with positive magnetostriction is explained by the structural-phase contrast of the steel. Magnetically soft areas of ferrite alternate with more magnetically hard areas of cementite. In this case, the force lines of residually magnetized cementite plates, whose coercive force H_C is of the order of 80–240 A/cm [16], can short-circuit through the magnetically soft areas of ferrite ($H_C = 2$ A/cm) immediately adjacent to it, and can have antiparallel magnetization. During stretching, the reverse magnetization of the magnetically soft sections in the reverse field of the magnetically open rigid phases saturates faster than the direct magnetization of the magnetically rigid sections of the sample that have a small positive magnetostriction constant. Therefore, in general, the resulting magnetization of the material decreases.

In the hardened state, the microstructure of 30Kh13 steel consists of martensite, a small amount of residual austenite and chromium carbides of the type $M_{23}C_6$. Tempering of quenched steel from 400°C leads to the decay of martensite and the appearance of pearlite (sorbitol, troostite), as evidenced by the increase in saturation magnetization [17]. At higher temperature, martensite disintegrates into a ferrite-carbide mixture, which manifests itself in a decrease in coercive force and an increase in magnetostriction [12,15]. Thus, as the tempering temperature increases, the magnetic contrast of the material increases, i.e., a condition that contributes to the appearance of negative PMR.

In the work jcite18, it was shown on U10 B- hypereutectoid steel, that developing of structure of „fresh“ and briefly tempered at 650°C martensite occurs under high load multicycle tensile. It was found that the cementitic plates in the

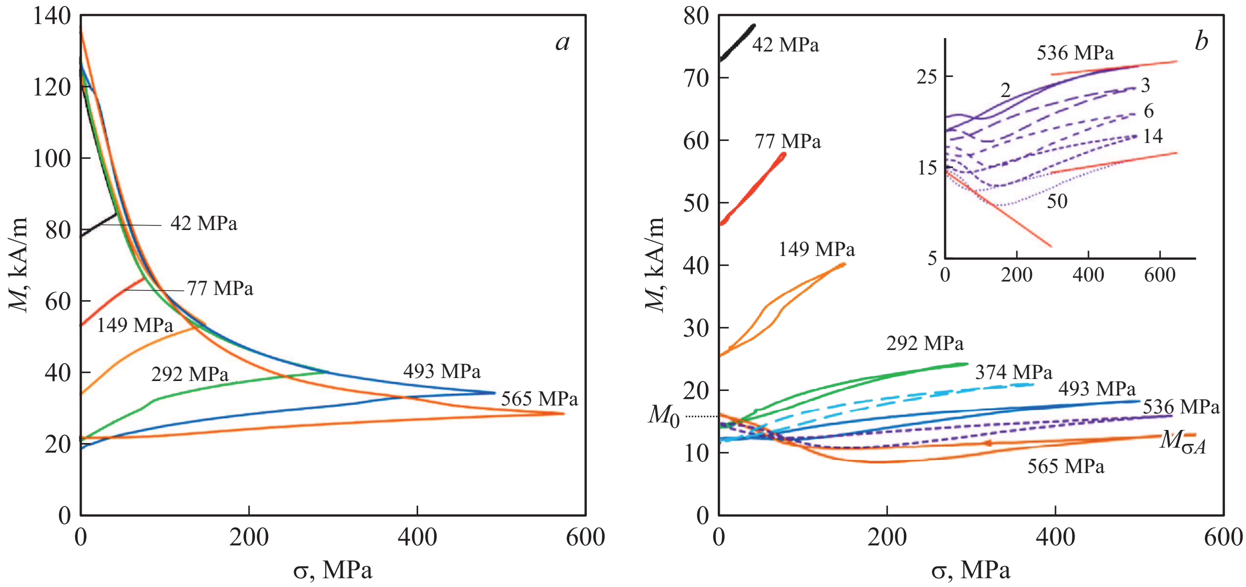

Figure 2. Dependence of residual magnetization on tensile stress for different loading amplitudes on sample 1 with 600°C tempering. The first (*a*) and last (fiftieth) (*b*) cycles of the series are given. For a load of 536 MPa some intermediate cycles are shown (in inset).

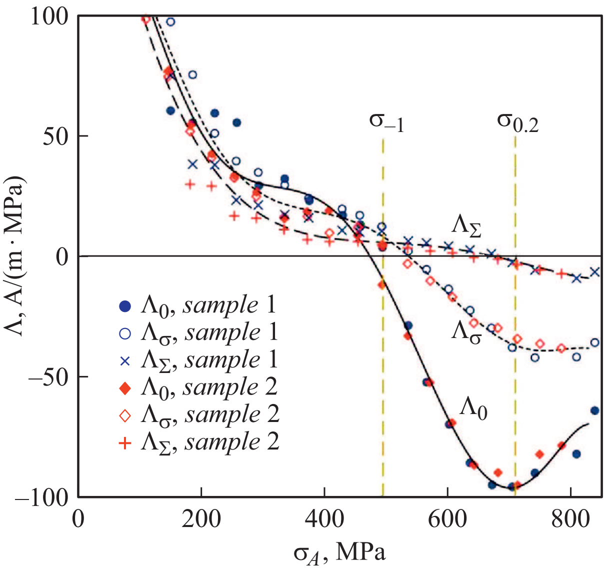

Figure 3. The nature of the loading amplitude effect on the magnetoelastic sensitivity Λ.

thin-plate martensite are fragmented, the fracture sites are replaced by a ferrite phase (polygonization occurs) with a high concentration of dislocations. As a result, the demagnetizing factor of fragmented cementitic hard magnetic plates increases. This leads to the appearance of additional magnetic scattering fields of cementite, increasing (inside the ferrite) the area volume with reverse magnetization. As a consequence, there is a negative piezoeffect, which will intensify as the exposure cycles are built up.

Thus, the observed changes in the characteristics of the piezomagnetic effect in the vicinity of the endurance limit of the material can be explained by the mechanism of inverse fields of rigid magnetic phases, which should only increase during fatigue degradation.

The research findings can be summarized as follows: 1) first time inversion of piezomagnetic effect of residual magnetization under low cycle loading of 30Kh13 steel hardened and tempered at 600°C was found; 2) it was shown that piezomagnetic effect is very sensitive to fine structural changes of 30Kh13 steel under loadings and can be used for control of fatigue degradation of 30Kh13 steel products.

Conflict of interest

The authors declare that they have no conflict of interest.

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