The influence of zero-to-tension loading on magnetic and acoustic properties of 08G2B hot-rolled steel

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Abstract. The paper reports on the results of studying the effect of the number of zero-to-tension loading cycles, with an amplitude approximately corresponding to conventional yield strength, on the acoustic and magnetic parameters of the 08G2B hot-rolled pipe steel, including its longitudinal and transverse magnetostrictions. The parameters uniquely varying with the number of cycles have been determined, and this principally enables these parameters to be used for the development of nondestructive methods of testing fatigue degradation in the material of structures made of the steel under study.

1. Introduction

Material fatigue is the main reason for the destruction of machine parts and structural elements [1–3]. Therefore, estimating the level of metal fatigue degradation is a crucial problem, which still remains unsolved despite the numerous publications on this subject, see, e.g., [4–6]. At the same time, nondestructive testing methods, particularly magnetic and acoustic ones, have proven to be effective in testing the stress-strain state and damage of various steel products and in estimating their residual life after heat treatment and under static deformation following various patterns [7–10]. It is of great interest to study the potential of magnetic structuroscopy and acoustic methods as applied to the estimation of the fatigue degradation of structural steels.

The paper aims at studying the effect of zero-to-tension cycling, with an amplitude approximately corresponding to conventional yield strength, of specimens made of the hot-rolled 08G2B pipe steel on the behavior of a number of their magnetic parameters, including longitudinal and transverse linear magnetostrictions, and acoustic parameters in order to investigate the applicability of magnetic and acoustic methods to estimating the condition of the metal of structures working under cyclic loading.

2. Experimental procedure and materials

The 08G2B hot-rolled pipe steel was used as a research object. Flat test specimens with heads were cut out of a longitudinally welded pipe, sized 1420×15.7 mm, along the rolling direction. The gauge part of the specimens had a cross section of 6×34.6 mm and was 100 mm long. Having been made, the specimens were annealed in vacuum at a temperature of 700 °C for 3 hours in order to relieve inner stresses.

The mechanical characteristics of the specimens were determined according to GOST 1497-84 under static tension on a Tinius Olsen Super L60 universal testing machine. They are as follows for
the 08G2B steel: a conventional yield strength of 280 MPa; an ultimate tensile strength of 535 MPa; an elongation at rupture of 30%. The loading diagram is presented in figure 1.

The specimens were then cyclically tested under zero-to-tension loading with an amplitude of 300 MPa, which is slightly above the value of conventional yield strength, with a frequency of 3 Hz. The number of cycles \( n \) was varied. As a result, specimens having undergone 0, 30, 50, 100, and 300 thousand cycles were obtained.

3. Results and discussion

Figure 2 shows the magnetic characteristics (coercive force, residual induction and maximum permeability) of the specimens after cyclic zero-to-tension testing, measured in a closed magnetic circuit on both the major and minor magnetic hysteresis loops and reduced to the corresponding initial values of the magnetic parameters in the no-load state, depending on the number of cycles \( n \). The dependences of the magnetic characteristics of the minor magnetic hysteresis loops on the number of cycles are in a good qualitative agreement with those obtained on the major loops. As the number of cycles increases, the magnetic characteristics vary monotonically, the most intensive change in their values being observed at the initial stage of cyclic loading. Thus, the values of residual induction and maximum magnetic permeability decrease by more than 29% on the major magnetic hysteresis loops, and the coercive force increases by 34%. Subsequently, the magnetic characteristics vary to a lesser extent, within 10%.

Measurements in a closed magnetic circuit are hard to implement in practice, whereas the use of attached transducers enables a wide range of problems to be solved both under laboratory conditions and in production. The results of measurements made with the use of attached transducers are depicted in figure 3. The figure shows the values of the coercive force \( H_{ce} \), the number of Barkhausen jumps \( N \), and the rms values of magnetic Barkhausen noise voltage \( U \), measured along and across the loading axis, as dependent on the number of loading cycles. It follows from figure 3a that, in the case of longitudinal measurements, the dependence of \( H_{ce}(n) \) (figure 3a, curve 1) is qualitatively similar to the dependences of the coercive force on the \( n \) in figure 2; namely, \( H_{ce} \) increases with \( n \). By contrast, the coercive force measured in the longitudinal direction varies non-uniquely, figure 3a, curve 2.

The increase in the values of the longitudinal coercive force after cyclic loading from those in the unloaded state is attributable to significant residual compressive stresses appearing in a large number of grains along the tension axis under stress relief after testing for zero-to-tension cycling [11-14]. Herewith, prerequisites arise for the formation of the easy-magnetization-plane magnetic texture, when it is energetically more advantageous for the spontaneous magnetization vectors to be arranged in the plane perpendicular to the tension axis and hence to the magnetizing and switching field; consequently, the magnetization reversal processes are hampered, and this is what increases the coercive force and, accordingly, decreases residual induction and maximum magnetic permeability. Residual tensile stresses are of importance in the direction normal to the tension axis, and this is what
causes the non-unique behavior of $H_{ce}(n)$ when measurements are made in the transverse direction (curve 2, figure 3a) since, in this case, the measurement scheme corresponds to the measurements of the magnetic characteristics in the longitudinal direction under tensile loading.

The rms values of Barkhausen noise voltage $U$ as a function $n$ of behave oppositely to $H_{ce}(n)$. When the measurements are made along the tension axis (figure 3c, curve 1), these values decrease monotonically with the increasing number of testing cycles (the increment is 80 % from the initial value without loading); when the measurements are made in the transverse direction, the values of $U$ vary non-uniquely as $n$ increases, with the appearance of a peak (figure 3c, curve 2). The number of Barkhausen jumps changes insignificantly with increasing $n$ in both longitudinal and transverse directions, figure 3b.

Figure 2. Relative variation of magnetic parameters (coercive force (curves 1), residual induction (curves 2), and maximum magnetic permeability (curves 3)) measured in a closed magnetic circuit as dependent on the number of loading cycles $n$: (a) – on the major magnetic hysteresis loop; (b) – in medium fields; (c) – in weak fields.

Figure 3. Coercive force $H_{ce}$ (a), the number of Barkhausen jumps $N$ (b), and the rms values of voltage $U$ (c), measured with the use of attached magnetic devices, as dependent on the number of cycles $n$: curves 1 – measurements made along the loading axis; curves 2 – measurements made across the loading axis.

Figure 4 shows the field dependences of differential magnetic permeability $\mu_d(H)$ for the specimens tested for zero-to-tension cycling with different numbers of cycles $n$. The dependence $\mu_d(H)$ has one peak for the undeformed specimen and two peaks for the cyclically loaded specimens. The first peak is observed in negative fields, and the second peak is found in positive ones. The magnitudes of the peaks of $\mu_d(H)$ localized in negative fields noticeably exceed those of the peaks observed for the deformed specimens in positive magnetic fields. Note that, as the number of cycles increases, the peak height in the negative fields on the field dependence decreases and its localization shifts towards stronger fields. At the same time, on the curves $\mu_d(H)$ for the cyclically loaded specimens, the peak located in positive fields becomes more pronounced as $n$ increases, and its location also shifts towards stronger fields. The results agree well with the data reported in [15], where the physical nature of the peaks in positive fields on the field dependences of differential magnetic permeability measured on uniaxially deformed steel specimens is explained.
Thus, the value of strain accumulated in a product under cyclic loading can be inferred from the presence, location and height of the peak in positive fields on the field dependences of differential magnetic permeability.

Figure 5 shows the dependences of linear longitudinal $\lambda_\parallel$ and transverse $\lambda_\perp$ magnetostrictions on applied magnetic field for specimens tested for zero-to-tension cycling with different numbers of cycles $n$.

In the initial state, when $n = 0$, the longitudinal magnetostriction first increases to a maximum with growing magnetic field strength, then decreases, reaches zero, and continues decreasing, this time with a negative sign (curve 1 in figure 5a). For the cyclically loaded specimens (curves 2 and 3 in figure 5a), $\lambda_\parallel(H)$ is positive at all the values of magnetic field strength. Note that, as the number of cycles increases, the area of the positive portion of the field dependence of magnetostriction increases, and so does the magnitude of its peak.

For the unloaded specimen ($n = 0$), the transverse magnetostriction $\lambda_\perp(H)$ first decreases to a minimum with growing magnetic field strength, then increases, reaches zero, and continues increasing with a positive sign (curve 1 in figure 5b). The transverse magnetostriction of the cyclically loaded specimens is negative in the entire range of magnetic field strength variation. The area of the negative portion of the transverse magnetostriction increases with $n$, and so does the absolute value of its minimum. This behavior of $\lambda_\parallel(H)$ and $\lambda_\perp(H)$ is inherent in $\alpha$-iron-based magnets affected by compressive stresses [16], this being indicative of the formation of residual compressive stresses after cyclic loading along the axis of cyclic tension and residual tensile stresses in the transverse direction.
Experiments to determine the velocity of the propagation of longitudinal and transverse elastic waves (the method of the determination is given in [17, 18]), the results of which are shown in figure 6, showed that the velocity of the longitudinal wave is practically independent to the orientation of the phase array. In addition, the velocity of the longitudinal wave within the error does not change with the number of loading cycles.

As opposite to the case of a longitudinal wave, a noticeable anisotropy of the velocity of transverse wave propagation was found with a different orientation of the phase array. In the case when it is oriented along the direction of load, the velocity of the transverse wave is about 1 % higher than with the transverse arrangement of the phase array. However, it should be noted that after 300 thousand cycles of the loading by means of zero-to-tension stress cycle, this anisotropy disappears. The velocity of the transverse wave propagation at different orientations of the phase array monotonously decreases at more than 6 % with an increase in the number of loading cycles from 0 to 300 thousand. This behavior of the elastic wave velocity corresponds to modern concepts of acoustoelasticity [19]: with an increase in the number of loading cycles, that is, the accumulation of fatigue damage material, the number of scattering centers of elastic waves increases and, accordingly, the velocity of the propagation of these waves decreases. This circumstance makes it possible to consider the magnitude of the velocity of a propagation of transverse elastic wave as a promising informative parameter of the accumulation of fatigue degradation of a material during zero-to-tension cyclic loading with the magnitude approximately corresponding to conventional yield strength of the material.

![Figure 6. The velocity of longitudinal wave (a), the velocity of transverse wave (b) as dependent on the number of cycles n: curve 1 – measurements made along the loading axis; curves 2 – measurements made across the loading axis.](image)

4. Conclusion
The paper has presented the results of studying the effect of the number of zero-to-tension loading cycles with a magnitude approximately corresponding to conventional yield strength on the magnetic and acoustic parameters of the 08G2B hot-rolled pipe steel, including longitudinal and transverse magnetostrictions.

It has been found that the rms values of magnetic Barkhausen noise voltage and the values of velocity of transverse wave vary uniquely with the increasing number of cycles; this enables these parameters to be used for the development of methods for estimating the condition of the metal of structures working under cyclic loading.

The presence of extrema in the region of positive fields on the field dependences of differential magnetic permeability, the value of the fields at which they are formed, and the magnitude of the extrema allow one to evaluate the strain accumulated in a cyclically loaded product.

It has been demonstrated that, as the number of zero-to-tension cycles grows, the field dependences of the longitudinal ($\lambda_1$) and transverse ($\lambda_2$) magnetostrictions of the steel behave the same way as
under static compression; namely, for the dependence $\lambda_\parallel(H)$ it is the positive portion that increases with the number of cycles, whereas the transverse dependence has an increasing negative portion.

**Acknowledgments**

The work was performed within the framework of the state assignment, theme No. AAAA-A18-118020790148-1 and supported by the 18-10-1-40 project of the Ural Branch of the RAS (No. AAAA-A18-118020790143-6), and supported by the 18-9-1-20 project of the Ural Branch of the RAS (No. AAAA-A18-118020790149-8). The equipment of the “Plastometriya” collective use center was used in the study.

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