Magnetic Methods for Estimating Elastic Strains in Steel Structural Members
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Abstract
To develop techniques for estimating stresses in steel structural members is an urgent problem of nondestructive testing, and its solution will reduce the risks of industrial disasters considerably. Loading conditions simulating pipeline operation have been implemented experimentally. Tubular specimens were used to study the effect of elastic deformation by uniaxial tension (compression) and torsion under hydrostatic pressure on the magnetic characteristics (coercive force, residual induction, maximum magnetic permeability) of some structural steels and the distribution of critical magnetic fields in them. The dependences obtained demonstrate that these characteristics can in principle be used to test stresses in steel structures, e.g. pipelines, magnetically.

Keywords: Magnetic methods, critical magnetic fields, elastic stress, pipeline

Introduction
The development of techniques for estimating stresses in steel structural members is an acute challenge for nondestructive testing; a solution to be found will reduce the risks of industrial accidents considerably. The effect of elastic and plastic strains on the magnetic properties of steels are discussed in many papers; however, only a small number of scientific works deal with measurements of the magnetic characteristics of a material being deformed. Besides, those works cover mainly such modes of loading as uniaxial tension or compression, and, less frequently, torsion. For instance, the behaviour of magnetic Barkhausen noise in different stages of uniaxial tension directly in the course of loading was discussed in [1]; the in-situ measurement of the effect of plastic strain on a set of magnetic characteristics of pearlitic steels was made in [2].

Instances of pure uniaxial tension, compression or torsion can almost never be found in actual practice. For example, besides stresses from internal pressure, pipelines suffer various external effects, namely, thermal strains, earth deformation, seismic phenomena etc. Therefore it is particularly urgent to study the effect of combined loads on the magnetic behaviour of ferromagnetic materials. Coercive force and such structure-sensitive magnetic characteristics as residual induction (magnetization) and maximum magnetic permeability are representative of the integral properties of a ferromagnetic material and characterize its general resistance to external effects [3]. More exact information on the processes of magnetization and magnetization reversal, on the interaction of domain walls with certain types of defects can be obtained from studying the resistance of a specific magnetic state, or a number of magnetic states, to magnetic and electromagnetic fields and elastic strains.

Loading conditions modeling the operation of actual structures, e.g., pipelines, have been realized within this work. Hollow cylindrical specimens were used to study the effect of elastic deformation by uniaxial tension (compression) and torsion, with simultaneous hydrostatic pressure, on the pattern of the distribution of critical magnetic fields during magnetization and magnetization reversal, the form of the hysteresis loops and magnetic characteristics (coercive force, residual induction, maximum magnetic permeability) of
chromium-nickel-copper structural steels.

Experimental details

To conduct investigations, continuous and hollow cylindrical specimens were made of two Cr-Ni-Cu structural steels, similar in composition and properties, with 3% and 4% nickel content. Besides the steels contained ≈ 0.1 % C, ≈ 1 % Cr, ≈ 1 % Cu. The tests were performed on a unique device enabling one, simultaneously, to effect tension (compression) and torsion and exert hydrostatic pressure in the inside hollow of a specimen. Besides, when being torsion-tested, hollow specimens have a lower heterogeneity of shear strains over the cross section as compared with continuous cylinders.

Permeameter magnetic measurements were made under applied loading. The tests were performed in the elastic strain region. Under combined loading, the normal (σ) and tangential (τ) stresses did not exceed 250 MPa in magnitude, and the pressure (P) in the inside hollow of the specimen did not exceed 50 MPa.

Residual induction $B_r$ was determined on the major magnetic hysteresis loops with magnetic field strength $H$ up to 600 A/cm. Maximum magnetic permeability $\mu_{max}$ was obtained from the initial magnetization curve. The coercive force was determined on the major magnetic hysteresis loops $H_c$ and on the minor cycles during magnetization to maximum magnetic inductions of 0.4 T ($h_c^{0.4}$) and 0.05 T ($h_c^{0.05}$).

To study the distribution of critical fields in the specimens under magnetization and magnetization reversal, the values of residual induction $B_r(H)$ and $B_d^-(H)$ were measured, respectively, from the minor loops at different magnetization fields and from the descending hysteresis branch. The curves obtained by differentiating $B_r(H)$ and $B_d^-(H)$ with respect to $H$ represent the distributions of the critical fields of the ferromagnetic material, which are sometimes termed magnetic rigidity spectra [4]. The areas under the curves $\frac{\Delta B_r}{\Delta H B_{rmax}} (H)$ and $\frac{\Delta B_d^-}{2\Delta H B_{rmax}} (H)$ characterize the relative volumes of the ferromagnetic material that has undergone magnetization (primary magnetic rigidity spectrum) or magnetization reversal (secondary spectrum) in the field of a given strength $H$. The positions of the peaks on the field dependences $\frac{\Delta B_r}{\Delta H B_{rmax}} (H)$ and $\frac{\Delta B_d^-}{2\Delta H B_{rmax}} (H)$ are close in values to the coercive force, and they correspond to the magnetic field where the processes of irreversible magnetization or magnetization reversal are the most intensive.

Results and discussion

Magnetic rigidity spectra for the 4% Ni steel are shown in Fig. 1. It follows from the figure that the half-width (the width of the distribution curve measured at the half of the maximum peak value) of the secondary spectra (Fig. 1 b, d) is smaller than the half-width of the primary ones (Fig. 1 a, c), i. e., the process of magnetization reversal is a little more intensive than magnetization from the statically demagnetized state.

As compressive stresses grow (Fig. 1 a, b), the peaks of magnetic rigidity spectra shift to the region of stronger fields, the values of the peaks of magnetic rigidity spectra decrease, and the half-width increases. It means that, in weak magnetic fields, the relative magnetized volume is...
much smaller under compressive loading coaxial with the magnetic field than if magnetization is without loading.

Tensile stresses (Fig. 1a, b) have an opposite effect, namely, in a magnetic field of a given strength, growing $\sigma$ is accompanied by an increase in the relative magnetized volume of the ferromagnetic material. For instance, in the field of 5 A/cm, 10% of the material becomes magnetized without external loading and less than 5% under compressive loading; under tension, the same magnetic field magnetizes up to 40% of the material volume.

![Figure 1. The primary (a, c) and secondary (b, d) spectra of the magnetic rigidity of chromium-nickel steel with 4% Ni content when tested for compression/tension (a, b) and torsion (c, d). The insets show the initial portions of the magnetic rigidity spectra.](image)

This influence of normal stresses on the processes of magnetization and magnetization reversal results from the magnetoelastic effect implying that, if the signs of magnetostriction ($\lambda_s$) and stresses ($\sigma$) coincide, the effect of stresses facilitates the processes of magnetization and magnetization reversal; as this takes place, the coercive force decreases, whereas the residual induction and the maximum magnetic permeability increase [5]. If the signs of $\lambda_s$ and $\sigma$ are different, the applied stresses hamper the processes of magnetization and magnetization reversal.

It is obvious from Fig. 1b that, when magnetization reversal occurs under weak magnetic fields, close to the magnetic pole of the Earth (about 1 A/cm), compressive stresses promote magnetization reversal, whereas tensile stresses oppose it, see the initial portions of the secondary spectra in Fig. 1b. This may be due to different initial states (the statically
demagnetized state for magnetization and residual magnetization for magnetization reversal), i.e., due to different initial distribution of the magnetic phases.

The behaviour of the magnetic rigidity spectra in torsion testing (Fig. 1 c, d) is qualitatively similar to that for tension, namely, the peak of the magnetic rigidity spectra grows with tangential stresses and shifts to the region of weaker fields, and the distribution half-width decreases.

The behaviour of the magnetic rigidity spectra for the 3% Ni steel under elastic tension, compression and torsion practically coincides with the behaviour of the spectra for the 4% Ni steel. Therefore the magnetic rigidity spectra under internal pressure were studied only for the 3% Ni steel. The results of uniaxial compression testing under internal pressures \( P \) of 0 and 16 MPa are presented in Fig. 2. As the compressive stress grows, the peaks of the primary magnetic rigidity spectra shift into the region of stronger magnetic fields, the magnitude of the peaks of the magnetic rigidity spectra decreases, and the half-width increases.

Hydrostatic pressure has a similar effect on the primary magnetic rigidity spectrum, i.e., the processes of magnetization and magnetization reversal are less intensive as the pressure grows. This is attributable to the fact that the internal pressure causes compressive radial stresses \( \sigma_r \) and tensile circumferential stresses \( \sigma_\theta \), acting in the plane perpendicular to the magnetization axis.

Maximum stresses arise on the inside cylinder wall, their values at the highest test pressure of 50 MPa being \( \sigma_r = -50 \) MPa, \( \sigma_\theta = 178 \) MPa. That is, hydrostatic pressure promotes the formation of the magnetic texture [5] with the predominant magnetic moment orientation perpendicular to the specimen axis. When the hydrostatic pressure changes, in the secondary spectrum there is some difference from the instance of compression, namely, as the pressure grows, the peak of the secondary spectrum shifts into the region of weaker fields, which was not the case with uniaxial compression.

Figure 3 shows the major (upper row) and minor (lower row) loops of magnetic hysteresis for the 3% Ni steel at various types of elastic strain (\( M \) is magnetization, \( \mu_0 = 4\pi \times 10^{-7} \) H/m is a magnetic constant). The compressive load coaxial with the magnetic field produces a magnetic texture hampering magnetization and magnetization reversal in moderate and strong fields. Consequently, the coercive force increases and the magnetic permeability decreases, see Fig. 3 b. The slope of the magnetization curve also becomes milder in weak magnetic fields, see Fig. 3 g. However, on the whole, the minor loops obtained under magnetization up
to the maximum induction of 0.05 T become narrow with increasing compressive stresses, whereas the major loops widen.

Tensile stresses (Fig. 3 c) lead to the formation of a magnetic texture facilitating magnetization along the specimen axis and yield a narrow hysteresis loop, close to “rectangular”. The minor loops measured in weak fields, grow wider with increasing tensile stresses, its initial portion being steeper (Fig. 3 h).

The differences in the behaviour of the coercive force and the area of the major and minor hysteresis loops result from different mechanisms of the formation of hysteresis in strong and weak fields.

The coercive force measured on the minor loops in weak fields (Fig. 3 i) increases as in the case of tension. Yet, on the major loops for torsion (Fig. 3 d), as in the case of compression, a decrease in residual induction relative to the initial state is obvious.

Hydrostatic pressure affects the hysteresis loop shape only slightly (Fig. 3 e, j), and this due to relatively small stresses caused by internal pressure. These stresses lie in the plane perpendicular to the magnetization axis. Therefore behaviour of the hysteresis loops is the most similar to that in the case of torsion, when the stresses are non-coaxial with the magnetizing field.

Since torsion simultaneously causes tensile and compressive stresses directed at an angle of 45° to the magnetization axis, there appear factors causing magnetic textures of various types. The coercive force measured on the minor loops in weak fields (Fig. 3 i) increases as in the case of tension. Yet, on the major loops for torsion (Fig. 3 d), as in the case of compression, a decrease in residual induction relative to the initial state is obvious.

Figure 4 presents the values of the coercive force measured on the major magnetic hysteresis loops (Fig. 4 a), on the minor loops in moderate fields (Fig. 4 b) and in the Rayleigh region (Fig. 4 c), as well as $B_1$ and $\mu_{\text{max}}$, as functions of normal stresses for 3% Ni steel. These dependences can be viewed as resulting from the formation of the magnetic texture of stresses. As compressive stresses grow, $H_c$ increases, $B_t$ and $\mu_{\text{max}}$ decrease. With growing tensile stresses, $H_c$ decreases, $B_t$ and magnetic permeability increase.

It is obvious from Fig. 4 c that the coercive force $h_c^{0.05}$ measured on the minor cycles obt
at maximum induction of 0.05 T (the Rayleigh region), grows monotonically with increasing normal elastic stresses, whereas $H_c$ and $h_c^{0.4}$ (fig. 4 a, b) decrease with increasing tensile loading. Qualitatively similar results were obtained earlier in [6] for the 4% Ni steel, close in the composition, tested for uniaxial tension, compression and torsion.

It follows from Fig. 4 that, under uniaxial tension (compression), stresses caused by internal pressure have an insignificant effect on $H_c$ (5% variation), although they have a much greater effect on $B_r$ and $\mu_{\text{max}}$, namely, as pressure rises from 0 to 50 MPa, these characteristics decrease by about 20%.

The coercive force (on the major loop, in moderate fields and the Rayleigh region), $B_r$ and $\mu_{\text{max}}$ of the 3% Ni steel as functions of tangential stresses are shown in Fig. 5. As distinct from the case of normal stresses, in strong fields and the Rayleigh region there is no principal difference in the dependences of the coercive force. This may be because the stresses arising under torsion are not coaxial with the vector of the magnetizing field. Not only $H_c$ and $h_c^{0.4}$, but also $h_c^{0.05}$ increase with growing tangential stresses. Residual induction tends to decrease, though these changes are close to the measurement error (less than 5% variation). The quantity $\mu_{\text{max}}$ behaves nonmonotonically, i.e., it increases with $\tau$ rising to 100 MPa, and it decreases with a further growth of tangential stresses.

Under tangential stresses, as distinct from the case of tension (compression) and pressure combined, hydrostatic pressure has a noticeable effect on all the magnetic characteristics, including $H_c$, whose change reaches 10% as the internal pressure increases from 0 to 50 MPa. In the set of the major magnetic hysteresis loops of the steels tested, on the descending and ascending hysteresis branches, regions of the stability of the magnetic state against mechanical stresses can be observed, where magnetization remains practically unchanged with varying applied stresses. The major magnetic hysteresis loops for the 4% Ni steel are shown in Fig. 6 a as an example. In the field of 9.5 A/cm (modulo) there is a region of the stability of the magnetic state against mechanical stresses. The relation between magnetization and compressive stresses at the field strengths mentioned is demonstrated in Fig. 6 c. The variation of the curve does not exceed the measurement error. Regions of the
kind are observed under magnetization not only on the major hysteresis loops, but also on the minor cycles. For instance, in Fig. 6 b, on the loops measured in weak magnetic fields there is a region of the stability of the magnetic state against elastic stresses under a magnetic field of about 0.57 A/cm. The value of magnetization in this field remains almost unchanged under compressive loading, see Fig. 6 d. Since actual objects of testing are practically never in a demagnetized state, the existence of these stability regions must be taken into account. When the magnetic state of an object corresponds to be stability region, magnetic testing of mechanical stresses is very complicated.

Figure 5. The magnetic behaviour of the 3 % Ni steel as dependent on tangential stresses

Figure 6. The evolution of magnetic hysteresis loops for the 4% Ni steel under compression: major loops (a), the Rayleigh region (b); magnetization as dependent on mechanical stresses in the stability region (c, d).
Conclusions

Studies have been made on the distribution of critical magnetic fields for magnetization and magnetization reversal and on the behaviour of the magnetic parameters (coercive force $H_c$, residual induction $B_r$, maximum magnetic permeability $\mu_{\text{max}}$) of structural chromium-nickel-copper alloy steels with 3 % and 4 % nickel content under elastic strain by uniaxial compression, tension, torsion and hydrostatic pressure. Compressive stresses hamper the processes of magnetization and magnetization reversal in moderate and strong magnetic fields: the peaks of magnetic rigidit spectra decrease and shift into the region of stronger fields, the coercive force increases, residual induction and maximum magnetic permeability decrease. Tensile stresses lead to opposite dependences. This effect of normal stresses on the processes of magnetization and magnetization reversal results from the formation of the magnetic texture of stresses.

The coercive force grows with increasing tangential stresses. Residual induction tends to decrease, though the change does not exceed 5 %. The quantity $\mu_{\text{max}}$ behaves nonmonotonically, namely, it grows as tangential stresses increase to 100 MPa, and it decreases with a further increase in the stresses. This behaviour is due to the fact that torsion causes simultaneous tensile and compressive stresses, and this gives rise to magnetic textures of different types in the material.

The effect of hydrostatic pressure on the magnetic characteristics is similar to that of shearing stresses. This may be because hydrostatic pressure causes a magnetic texture with magnetic moments predominantly oriented perpendicular to the specimen axis.

The values of the field strength at which magnetization is practically independent of applied external stresses have been found on a set of magnetic hysteresis loops. The existence of such stability regions must be taken into account in the magnetic testing of mechanical stresses.

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References