An investigation into the Effect of Elastic Deformation by Tension (Compression), Torsion and Hydrostatic Pressure on the Magnetic Characteristics of Pipe Steel

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Abstract: The paper studies the effect of elastic deformation by tension/compression, torsion, internal pressure and their combinations on the magnetic characteristics of X70 control-rolled engineering steel. A unique dependence has been established between stress intensity and coercive force at various values of the Lode parameter. To make the determination of the stress tensor invariants more reliable in case the type of loading is unknown, the velocity of acoustic wave propagation in the material is proposed to be used as an informative test parameter in addition to magnetic characteristics.

Keywords: elastic strain, pipe steel, magnetic characteristics

1. Introduction

It is an urgent problem of nondestructive testing to develop methods for evaluating stresses in steel structural components. The effect of elastic and plastic strains on the magnetic and acoustic properties of steels has lately been abundantly discussed in the literature, see, e.g., [1-8]; however, few studies have so far dealt with the variation of material characteristics directly during deformation. Besides, those papers discussed mainly such types of loading as uniaxial tension or compression and, less frequently, torsion.

For many steels, the dependence of coercive force and other hysteretic properties on elastic tensile stresses is nonmonotonic, and this excludes the possibility of testing the stress-strain state by one parameter.

In actual practice, there are not only uniaxial but also more complex types of loading. The effect of biaxial loading on magnetic characteristics is studied in a rather small number of papers [5-7]. Therefore it is particularly topical to study the effects of combined loading on the magnetic characteristics of ferromagnetic materials.

In some cases, the acting loads are partially known, and this facilitates the testing of the stress state as a whole [8]. The stresses induced by internal pressure in a pipe are easily determinable, since they depend only on the known quantities – internal pressure, pipe diameter and wall thickness.

This paper reports on studying the effect of elastic deformation by uniaxial tension (compression) and torsion with simultaneous pressure inside a hollow cylindrical specimen made of pipe steel X70 on its magnetic and acoustic characteristics.

2. Materials and experimental procedure

Hollow cylindrical specimens were made from control-rolled steel X70. The tests were performed on a unit enabling one, simultaneously, to effect uniaxial tension (compression), torsion, to produce hydrostatic pressure in the inside the cylinder and to measure the magnetic and acoustic characteristics in the course of loading.

Magnetic measurements were made under elastic deformation in a closed magnetic circuit.
The Rayleigh surface wave velocity was determined along the specimen axis by an ASTR self-circulation frequency measuring device.

The stresses were calculated in the assumption that the material is isotropic. The normal stresses $\sigma$ induced by tension/compression along the specimen axis were computed by the formula

$$\sigma = \frac{F}{\pi \left( R_{out}^2 - R_{in}^2 \right)},$$  \hspace{1cm} (1)

where $F$ is the load applied to the specimen. The measurement of the specimen cross section under elastic deformation was neglected.

Since the magnetic characteristics are measured in the whole bulk of the material, we will consider the volume-averaged values of tangential stresses,

$$\tau = \frac{\left( R_{out} + R_{in} \right)}{\pi \left( R_{out}^2 - R_{in}^2 \right)} T,$$  \hspace{1cm} (2)

where $T$ is the current value of the torque and $r$ ranges between $R_{in}$ and $R_{out}$.

The determination of mechanical stresses arising under the action of hydrostatic pressure is a solution to the classical Lame problem of a thick-walled tube. Due to the symmetry of applied loads, the stresses and strains are also symmetric relative to the longitudinal symmetry axis of the cylinder. Tensile circumferential stresses $\sigma_\theta$ and compressive radial stresses $\sigma_r$ arise under the action of internal pressure. Their values as functions of the radius $r$ are found by the formulae

$$\begin{align*}
\sigma_r &= \frac{R_{in}^2}{R_{out}^2 - R_{in}^2} \left( 1 - \frac{R_{out}^2}{r^2} \right) p \\
\sigma_\theta &= \frac{R_{in}^2}{R_{out}^2 - R_{in}^2} \left( 1 + \frac{R_{out}^2}{r^2} \right) p
\end{align*}$$  \hspace{1cm} (3)

Here $p$ is the value of hydrostatic pressure.

Since the specimen ends are rigidly fixed, torsion and hydrostatic pressure will cause longitudinal forces. However, the arrangement of the testing unit enables these forces to be determined and compensated by controlled axial load $F$ involved in Eq. (1).

When tension (compression), torsion and internal hydrostatic pressure are combined, the stress tensor in a cylindrical coordinate system has the form

$$A = \begin{pmatrix} \sigma_r & 0 & 0 \\ 0 & \sigma_\theta & \tau \\ 0 & \tau & \sigma_z \end{pmatrix}.$$  \hspace{1cm} (4)

To find the principal stresses $\sigma_k$ ($k = 1, 2, 3$), we solve the equation

$$\left| A - E \sigma \right| = 0,$$  \hspace{1cm} (5)

where $E$ is a unity matrix. After volume-averaging, the values of the principal stresses become

$$\begin{align*}
\sigma_k &= \frac{1}{R_{out}^2 - R_{in}^2} \int_{r=R_{in}}^{r=R_{out}} \sigma_i \, dr \\
\sigma_k &= \frac{1}{R_{out}^2 - R_{in}^2} \int_{r=R_{in}}^{r=R_{out}} \left[ \sigma_\theta + \sigma_c \pm \sqrt{\left( \sigma_\theta + \sigma_c \right)^2 + 4 \left( \tau^2 - \sigma_\theta \sigma_c \right)} \right] dr
\end{align*}$$  \hspace{1cm} (6)

where the subscripts $k$ acquire the values 1, 2, 3 from the condition $\sigma_1 \geq \sigma_2 \geq \sigma_3$. 
3. Model representations

3.1. The effect of stresses on the resultant magnetization of ferromagnetic materials

In the unstressed demagnetized state, the vectors of the domain magnetic moments are oriented randomly, and their total (resultant magnetization \( M \)) is zero. Without loading, affected by applied magnetic field \( H \), the vectors of the domain magnetic moments are arranged along the direction of this field, and the resulting magnetization assumes some nonzero value \( M \).

According to [9], a magnetic texture with domain magnetic moments oriented predominantly along the direction of applied loading is formed in materials with positive magnetostriction affected by tensile stresses. Therefore, to attain a required value of magnetization, it would suffice to apply a lower magnetic field than that for the unstressed state.

Under the action of compressive stresses coaxial with the field, most of the vectors of domain magnetic moments \( M \) are oriented in the plane perpendicular to the direction of loading.

Internal hydrostatic pressure induces tensile circumferential directions \( \sigma_{\theta} \) and compressive radial stresses \( \sigma_{r} \). According to (3), tensile circumferential stresses are the greatest in magnitude, therefore, affected by pressure, the vectors of domain magnetic moments will be arranged into a plane.

Tangential stresses under torsion \( \tau \) are equivalent to a couple of normal mutually perpendicular tensile and compressive stresses acting in the plane tangential to the cylinder at an angle of 45° to the specimen axis. Therefore, under the action of tangential stresses the resultant magnetization vector lies at an angle \( \alpha \) to the direction of the applied magnetic field [3]. Obviously, the projection of the resultant magnetization vector on the \( z \)-axis \( (pr_{z}M) \) is smaller than the magnitude of the resultant magnetization in the unstressed state. The higher the tangential stresses (and, hence, the angle \( \alpha \)), the smaller is \( pr_{z}M \).

In the instance of all the three loading types combined, the values of the principal stresses \( \sigma_{1}, \sigma_{2} \) and \( \sigma_{3} \) are calculated by Eq. (6). Depending on the values of applied stresses and the solid angle \( \beta \) of the cone of the easy magnetization axes, the change in the projection of the resultant magnetization vector \( \Delta M \) may be both negative (if compressive stresses prevail or the angle \( \beta \) is large enough) and positive.

In materials with negative magnetostriction mechanical stresses will cause effects opposite to those described above.

3.2. The effect of stresses on ultrasonic wave velocity.

According to [2], for all wave types, the stress dependence of wave velocity can be written in the general form as

\[
\nu = \nu_{0}(1 \pm \beta \sigma),
\]

where \( \nu_{0} \) is wave velocity at zero stresses, \( \sigma \) is acting mechanical stresses, \( \beta \) denotes the acoustic-elastic coefficient of vibration propagation velocity, which depends on the wave type, Lame and Murnaghan elastic constants.

This technique enables uniaxial tensile and compressive stresses to be evaluated, provided that the wave direction coincides with the direction of loading. However, if the stresses act in the plane perpendicular to the wave direction, the changes in the velocity are insignificant. This makes it possible to use the Rayleigh surface wave velocity together with the magnetic parameters for estimating the type of loading.
4. Results and discussion

Figure 1 shows coercive force and residual induction as dependent on applied stresses. With all the three loading types combined, the effect of tangential stresses diminishes that of normal stresses on all the magnetic characteristics considered. This is because tensile stresses tend to rotate the vectors of domain magnetic moments to be parallel with the specimen axis, compressive ones rotate them to the plane perpendicular to the axis, and tangential stresses make the magnetization vector lie at an angle $\alpha$ to the direction of applied magnetic field. The angle $\alpha$ ranges between 0 and 45° depending on the value of tangential stresses. As a result, when tension and torsion are combined, magnetization is directed at an intermediate angle $\beta$ ranging between 0 and $\alpha$, and when compression and torsion are combined, it is directed at an angle definitely exceeding $\alpha$. The larger the solid angle $\beta$, the smaller the projection of the resultant magnetization vector on the $z$-axis.

When all the three loading types are combined, an increase in the internal pressure leads to an increase in the coercive force and a decrease in residual induction and maximum magnetic permeability, whereas the forms of the curves representing magnetic characteristics as dependent on the combination of tension (compression) and torsion remain unchanged. This is attributable to the following: since the stresses caused by internal pressure lie in the plane perpendicular to the direction of magnetization, there are prerequisites for the predominant arrangement of the spontaneous magnetization vectors in this plane.

Figure 2. Stress intensity as dependent on coercive force
The stress state of the object is characterized by a tensor, the measurable magnetic quantities being scalar. Therefore attempts have been made to relate the magnetic characteristics to some scalar parameters characterizing the stress state. The parameter termed “stress intensity” characterizes the amount of stresses, and it is calculated by the formula

$$\sigma_i = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1}. \quad (8)$$

Here $\sigma_1, \sigma_2, \sigma_3$ are volume-averaged principal stresses calculated by Eqn. (4). The Lode parameter is customarily used in the mechanics of solids to characterize the type of the stress state,

$$k_{\sigma} = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}. \quad (9)$$

Figure 2 shows a “stress intensity – coercive force” diagram for various loading types. Knowing the loading type, one can construct the dependence $\sigma_i(H_c)$ by this diagram. It follows from the figure that the ensemble of points obtained under combined loading is found in the region bounded from below by the lines $\sigma_i(H_c)$ at $k_{\sigma} = -1$ (tension) and $k_{\sigma} = 1$ (compression). The case of pure shearing, when $k_{\sigma}$ is zero, schematically divides the region into two parts. When $H_c < H_c|_{k_{\sigma}=0}$, $k_{\sigma} < 0$, except the cases when internal pressure has a greater effect than tensile and torsional loads together. Similarly, it reasonably safe to suggest that $H_c > H_c|_{k_{\sigma}=0}$ informs of a positive Lode parameter. Although in the case of loading by internal pressure without other loads $k_{\sigma} = -0.82$, the relation between stress intensity and coercive force is practically identical to the case of pure shearing, not uniaxial loading as might be supposed.

Figure 3 shows the Rayleigh surface wave velocity as dependent on applied stresses for various types of deformation. In the case of combined loading, this parameter enables stresses acting along the specimen axis to be determined. Using the data presented in figs 2 and 3, one can determine the Lode parameter. Then, knowing the type of loading, one can evaluate acting stresses by the coercive force.
4. Conclusion

When tension (compression) and torsion are combined, the action of tangential stresses diminishes the effect of normal stresses on all the considered magnetic characteristics. As the internal pressure grows, the coercive force increases, whereas residual induction and maximum magnetic permeability decrease. The behavior of the $\sigma$ and $\tau$ dependences of the magnetic characteristics remains unchanged. The coercive-force dependence of stress intensity has been constructed for various values of the Lode parameter. The effect of stresses on the Rayleigh surface wave velocity has been determined. Under combined loading, coercive force and wave velocity enable the type and intensity of loading to be evaluated.

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References

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