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Magnetic methods for estimation of load and damage levels in X70 steel

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The paper studies the magnetic, mechanical and structural characteristics of X70 steel after controlled rolling. The coercive force H_c, residual induction B_r, maximum permeability μ_{max} and maximum permeability field $H_{\mu_{max}}$ measured in situ in the loaded or unloading steel magnetized in different directions about the pipe axis are analyzed for applicability as parameters from which the working tensile stress in a pipeline and its preceding overload with attendant transition to the plastic range can be determined. An approach is proposed for estimating the accumulated damage level in the steel under tension or torsion from the coercive force H_c and/or saturation magnetization J_{max}.

Keywords: control-rolled steel, magnetic characteristics, damage parameter

1. Introduction

Reliable operation of trunk pipelines requires efficient online assessment of their technical state and residual lifetime, and this implies defectoscopy of pipes, diagnostics of stress-strain states in most dangerous black spots, and estimation of the degree of metal degradation under the action of operational factors. Trunk pipelines are characterized by a high degree of uncertainty of the stress-strain state of their primary load-bearing member (pipe) and by complex modes of thermomechanical loading. The main loads for pipelines are internal pressures and longitudinal forces produced by the temperature difference in a linear pipeline section under different temperature conditions of their construction and operation [1]. At the same time, shear loads are also possible in pipelines due to soil mobility, floods, etc. In this context, of particular importance is to develop reliable tools and methods to estimate the load and damage levels of a pipeline that would allow recommendations for optimization of operating modes at the stage of development of pipeline capacity and conclusions to strength and safety of the system at the stage of overhaul-period renewal [2].

The applicability of magnetic (coercimetric) methods for estimation of the working stress in pipelines was demonstrated with traditional hot-rolled pipe steels such as St2, St4, and 17Mn1Si [3, 4]. However, most of steels for trunk pipelines are produced by controlled rolling in which increased strength and cold resistance are attained directly through deformation due to a decrease in temperature and an increase in reduction ratio at the final stages of rolling. The recrystallization and growth of deformed austenite grains thus greatly slows down, particularly in the presence of disperse carbonitride precipitates [1]. The decrease in final rolling temperature to the $(\gamma + \alpha)$ range results in ferrite grains with a high dislocation density and pronounced deformation texture [5], and this strongly affects the magnetic properties of metal and is to be taken into account in magnetic methods of estimation of pipeline states.

Certain of ways of estimating the damage level in metals from magnetic characteristics were outlined in our previous papers. However, we restricted ourselves to traditional hot-rolled steels under hydrostatic pressure and torsion [6, 7], or to alloyed steels under torsion [8]. This is because the damage level in torsion is easier to calculate than that in uniaxial tension; moreover, the magnetic properties under hydrostatic pressure were measured after tests of the specimens rather than in situ.

The objective of the work was to develop methods for estimating the working stress and the damage level in trunk gas pipelines made of control-rolled high-strength steel from magnetic characteristics measured under uniaxial tension and torsion.

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Table 1

Chemical composition of the examined X70 steel

Element mass fraction, %										
C	Mn	Si	S	P	Cr	Ni	Mo	V	Al	Nb
0.060	1.620	0.180	0.003	0.015	0.040	0.020	0.24	0.068	0.040	0.050

2. Test specimens and research technique

The material to be tested was X70 low-carbon steel microalloyed with niobium, vanadium and addition of molybdenum. The chemical composition of the steel is given in Table 1. According to the classification of the American Petroleum Institute, the X70 steel grade points to a yield strength of 70 ksi which corresponds to about 485 MPa [9]. Microalloying of low-carbon steel with vanadium and niobium in combination with controlled rolling ensures complex hardening of the steel due to grain refinement, pearlite fraction reduction and dispersion hardening [10]. We examined fragments of a helical pipe of diameter 1420 mm and wall thickness 21.6 mm used for construction of trunk pipelines with a strength factor of 0.72 under the conditions of frigid climate and high operating pressure (up to 9.8 MPa). The specimens were cut crosswise and longwise the rolling direction and crosswise and lengthwise the helical pipe axis, i.e., at an angle of ~40° to the rolling direction (Fig. 1).

The quintuple cylindrical specimens were loaded according to GOST 1497-84 (Russian State Standards) on a test machine at a maximum force of 50 kN and room temperature with simultaneous measurements of the magnetic characteristics in a closed magnetic permeameter circuit using a Remagraph C500 measuring system. The magnetic field was applied along the tension axis of the specimens with the inductance coil axis parallel to the tension axis. The internal magnetic field strength H was measured with a magnetic potentiometer. The hysteresis loop was recorded on the plane B–H (B is the magnetic induction) at a maximum internal field of 60 kA/m by storing 2500 points. The measurement error for the field and induction was no greater than ±3 %. The major hysteresis loops were used to determine the coercive force H_c, residual induction B_r, maximum permeability μ_{max} and maximum permeability field $H_{\mu_{max}}$. The principle of operation of the experimental facility for measuring the magnetic characteristics under loading is described in [11].

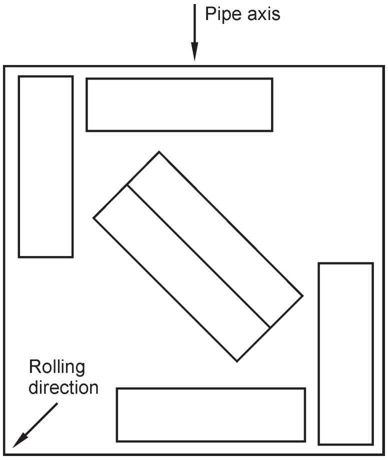

Fig. 1. Schematic of cutting of the specimens for mechanical tests

The elongation under tension was determined using a LaVision contactless strain measuring system. The LaVision system consists of a control computer and a video camera of resolution 1600 × 1200 with a pixel size of 7.4 μm and a filming speed of 30 frames per second. The system allows determination of the displacement and strain fields at the specimen surface under deformation from specimen images taken with the system.

The torsion angle was measured with raster displacement sensors fixed directly to the specimens. The tests were conducted up to fracture of the specimens. The velocity of the active grip was 1 mm/min or $360° \text{ min}^{-1}$.

The torsional shear strain Λ was determined on the hypothesis that the specimen cross-section under deformation has no radius distortion [12]; the torsional shear strain at the specimen surface is thus

$$\Lambda = \mathrm{tg}\varphi, \tag{1}$$

where φ is the slope of a guide mark on the specimen surface to the generatrix.

The mean shear strain over the specimen cross-section was determined by the formula [13]:

$$\tilde{\Lambda} = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R \frac{r}{R} \mathrm{tg}\varphi \, r \, \mathrm{d}\varphi \, \mathrm{d}r = \frac{2}{3}\Lambda, \tag{2}$$

where R is the specimen radius; r is the current radius variable from 0 to R.

The accumulated integral mean shear strain Λ_{sum} was estimated by summing over the strain of the previous deformation stages.

The microstructure was examined using a LEICA optical microscope with Materials Workstation software and a TESCAN scanning electron microscope with VEGA software.

3. Damage parameter

In mechanics, a characteristic of strain-induced defects is the damage parameter ω. According to the phenomenological theory of fracture [13], the damage parameter (the damage level) before the onset of deformation is taken equal to zero and by the time of fracture it is taken equal to $\omega = 1$.