Studying the effect of elastic-plastic strain and hydrogen sulphide on the magnetic behaviour of pipe steels as applied to their testing

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Abstract. The paper reports results of magnetic measurements made on samples of the 12GB pipe steel (strength group X42SS) designed for producing pipes to be used in media with high hydrogen sulphide content, both in the initial state and after exposure to hydrogen sulphide, for 96, 192 and 384 hours under uniaxial elastic-plastic tension. At the stage of elastic deformation there is a unique correlation between the coercive force measured on a minor hysteresis loop in weak fields and tensile stress, which enables this parameter to be used for the evaluation of elastic stresses in pipes made of the 12 GB pipe steel under different conditions, including a hydrogen sulphide containing medium. The effect of the value of preliminary plastic strain, viewed as the initial stress-strain state, on the magnetic behaviour of X70 pipe steels under elastic tension and compression is studied. Plastic strain history affects the magnetic behaviour of the material during subsequent elastic deformation since plastic strain induces various residual stresses, and this necessitates taking into account the initial stress-strain state of products when developing magnetic techniques for the determination of their stress-strain parameters during operation.

1 Introduction

Problems of estimating the degradation of the strength properties of pipe steels, especially when they operate in corrosion-active environments containing hydrogen sulphide, and diagnosing the stress-strain state of pipes are currently urgent in oil and gas industry. In hydrogen sulphide containing media, intensive hydrogenation of metal takes place, which causes pores filled with hydrogen, laminations and cracks. Note also that the effect of a corrosion-active medium on metals enhances under high residual stresses in products [1, 2]. However, such important parameter as the level of residual stresses in pipes is tested only in production, without regard for the fact that a pipe may suffer additional uncontrollable plastic deformation while being transported to the installation site and installed. As a result, the condition of pipes after pipeline laying may differ greatly from their condition at the

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moment they leave the production plant. This may result in higher material damage rates, higher probability of emergencies and a shorter service life of pipelines.

Nondestructive magnetic techniques are currently finding increasing application in diagnosing the stress-strain state of pipes. The development of these techniques was discussed in numerous studies, e.g. in [3-6], but practically all of them ignored the history of the preliminary plastic strain of the material.

This paper studies the effect of elastic-plastic tensile deformation and the effect of hydrogen sulphide on the magnetic characteristics of steel pipe specimens in order to substantiate the choice of informative parameters for diagnosing the condition of pipes in production and use. The history of the specimens was modelled by uniaxial plastic tension and holding in a hydrogen sulphide containing medium.

2 Experimental procedure and material

Test specimens of control-rolled pipe steel of strength class X70 (according to the API classification), cut out from a large pipe, and steel 12GB designed for operation in media with high hydrogen sulphide content are studied.

The effect of preliminary plastic strain on the magnetic behaviour of the specimens during subsequent elastic deformation is studied on X70 steel specimens cut out from a 1420 mm diameter pipe along the direction of rolling. In stage I, the specimens were subjected to uniaxial tension to various values of plastic strain δ, namely, 0.08, 0.23, 0.49 and 1.65%, with the determination of their magnetic characteristics. The loading–unloading diagrams for each specimen are presented in fig. 1. In stage II, the specimens plastically pre-deformed in stage I underwent elastic tension and compression, the magnetic characteristics being simultaneously measured in a closed magnetic circuit and with attached magnetic devices with the aid of the Remagraph C500 hysteresisgraph, the specimens being magnetised along the direction of applied loading. The specimens were deformed at room temperature.

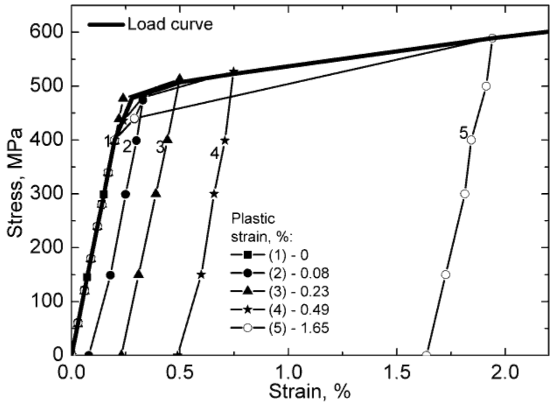

Fig. 1. Loading–unloading diagrams for the test specimens.

The effect of hydrogen sulphide on the magnetic properties of the 12GB steel was studied on specimens cut out lengthwise from a 114 mm diameter pipe, under conditions of elastic and plastic deformation by uniaxial tension at room temperature. Four sets of specimens were examined in the initial state and under the action of hydrogen sulphide lasting 96, 192 and 384 hours. The specimens were saturated with hydrogen sulphide at 20 °C in the A model medium according to the NACE TM0177-2005 standard.

Magnetic measurements were made in a closed permeameter-type magnetic circuit by means of the Remagraph C500 hysteresisgraph.

3 Results and discussion

3.1 Effect of preliminary plastic strain on the magnetic characteristics of the X70 steel

Figure 2 shows magnetic characteristics (coercive force H_c, residual induction B_r and maximum magnetic permeability μ_{max}) as dependent on tensile stresses, the dependences being obtained in the stage of plastic deformation to a certain level and under subsequent unloading. The magnetic behaviour of the specimens under tension agrees with the current ideas of the processes occurring in the magnetic structure of steels under force action. Similar results of studying the effect of elastic-plastic tension on magnetic behaviour were obtained earlier and discussed in [7, 8].

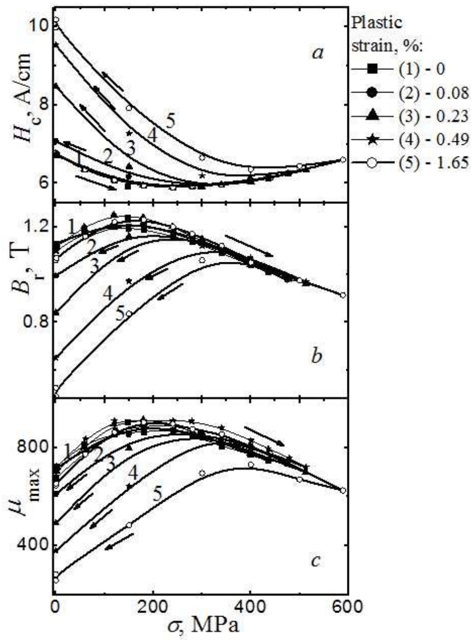

Fig. 2. Coercive force H_c (*a*), residual induction B_r (*b*) and maximum magnetic permeability μ_{max} (*c*) as dependent on tensile stresses under loading to different values of plastic strain followed by load removal: 0 (curve 1), 0.08% (2), 0.23% (3), 0.49% (4), 1.65% (5).

It follows from fig. 2 that, when the specimens are unloaded after plastic strain, the magnetic characteristics change irreversibly; the higher the value of plastic strain, the greater these irreversible changes. The higher values of the coercive force in the no-load state than those in the loaded state can be explained as follows: in the course of unloading, significant residual compressive elastic stresses arise along the direction of tension in a considerable number of grains; herewith, prerequisites appear for the formation of the "easy magnetization plane" magnetic texture, when it is more energetically advantageous for the spontaneous magnetization vectors to line up in the plane normal to the tension axis and hence to the magnetization and magnetization reversal fields; as a result, the magnetization reversal is hampered, and this increases the values of the coercive force and decreases the values of $B_r(\sigma)$ and $\mu_{max}(\sigma)$. These results agree with those obtained in [9], where they also reported a significant difference in the coercive force values for loaded and unloaded steel specimens under plastic tension.

For a vivid demonstration of the effect of plastic strain on the magnetic behaviour of the specimens, fig. 3 shows the values of magnetic characteristics after load removal, reduced to the values in the no-load state, as dependent on the value of plastic strain. The monotonic behaviour of the magnetic characteristics with growing plastic strain enables these parameters or their combination to be used to evaluate the strain state of a pipe which results from pipe manufacture, transportation and installation and which must be considered later on, when testing the stress-strain state during operation.

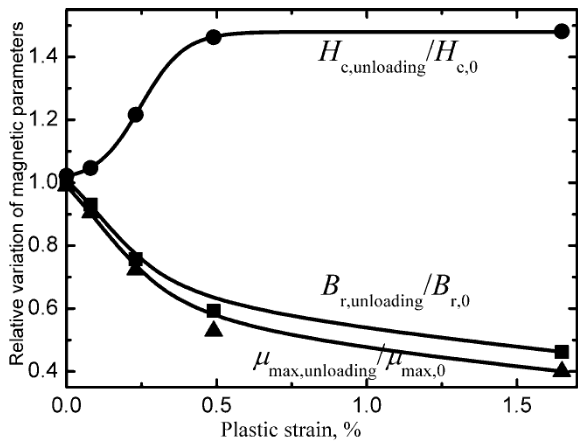

Fig. 3. Relative variation of magnetic parameters after load removal from the value of plastic strain.

3.2 Effect of elastic tensile/compressive strain on the magnetic characteristics of the X70 steel after preliminary plastic deformation

Figure 4 shows the magnetic characteristics of the specimens as dependent on applied stresses measured in a closed magnetic circuit under elastic tension/compression after previous plastic tension to various values.

Under elastic tension, the magnetic behaviour of specimens with different initial stress-strain states is identical; namely, when the tensile stress values increase, the magnetic characteristics change nonmonotonically, with extreme points. It follows from fig. 4 that the higher the value of plastic pre-strain, the higher the values of stresses matched by these extrema. The values of stresses at which there are minimum coercive force values (and, correspondingly, peaks on the dependences $B_r(\sigma)$ and $\mu_{max}(\sigma)$) are attributed to a partial compensation of a part of residual internal compressive stresses by external elastic tensile stresses [10, 11]. It is obvious that the higher the value of plastic pre-strain, the higher the level of residual internal compressive stresses; consequently, the higher the value of stresses at which the coercive force is minimum and the wider the range of applied elastic stresses where the magnetic behaviour is monotonic. Note that the applied stress dependences of the magnetic characteristics measured under elastic tension coincide, within the measurement error with similar dependences obtained under load removal. The reversibility of the changes in the magnetic parameters is characteristic of all the specimens, regardless of the value of their plastic pre-strain. These results agree with those obtained in [10].

Under elastic compression (see fig. 4), the dependences of the magnetic characteristics of the metal plastically pre-strained by tension to small values, below 0.23% (curves 1 and 2 in fig. 4), remain monotonic over the entire range of compressive stresses. For the compression of the specimens with plastic pre-strain of 0.23% and higher and, correspondingly, with a higher level of residual compressive stresses (curves 3 to 5 in fig. 4) there are extrema on the dependences $H_c(\sigma)$, $B_r(\sigma)$ and $\mu_{max}(\sigma)$. This is uncharacteristic of the magnetic behaviour of α-iron-based magnetic materials under elastic compression. Besides, irreversible changes of the magnetic parameters are observed for these specimens when the load is removed after elastic compression. The irreversible changes in the magnetic characteristics of the specimens with high values of plastic pre-strain may be due to the transition into the region of developed plastic strain of in metal regions with external compressive stresses imposed upon residual compressive stresses; as a result, the total stresses overshoot the yield stress. Besides, a decrease in the yield stress must be taken into consideration in the compression tests of the specimens subjected to plastic pre-tension (the Bauschinger effect [12, 13]). Under plastic compression, the "easy magnetization plane" magnetic texture collapses and, correspondingly, the processes of magnetization reversal along the direction of compression become easier. The latter, in turn, decreases the values of the coercive force; as a consequence, the curve $H_c(\sigma)$ corresponding to unloading after compression lies below the similar curve for loading. On the other hand, increased dislocation density under plastic strain must result in increased coercive force. Obviously, this circumstance is of secondary importance in the formation of the level of the hysteretic characteristics of the studied materials under compression.

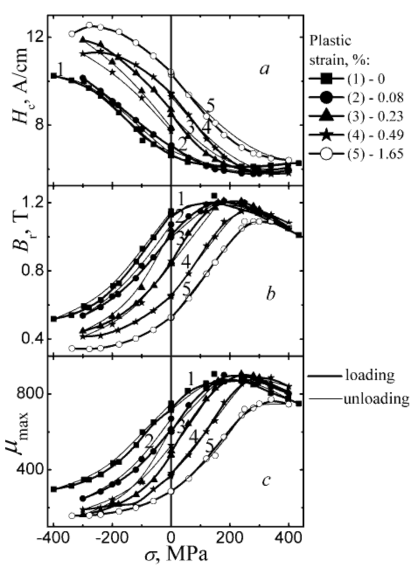

Fig. 4. Applied external stress dependences of coercive force H_c (*a*), residual induction B_r (*b*) and maximum magnetic permeability μ_{max} (*c*) measured in a closed magnetic circuit. The plastic strain values are 0 (1), 0.08% (2), 0.23% (3), 0.49% (4) and 1.65% (5).

In practice, it is easier to measure the magnetic parameters with the use of attached transducers, particularly, for testing large objects, such as large-diameter pipes. Test results obtained with the use of attached transducers are depicted in fig. 5 showing the values of the coercive force H_{ce} and the rms values of magnetic Barkhausen noise voltage U

(measured when the transducer is placed on the specimens along the direction of applied loading) as dependent on applied stresses. It follows from a comparison between fig. 4 and fig. 5 that in the tension region there is a qualitative similarity between the dependences $H_c(\sigma)$ and $H_{ce}(\sigma)$ obtained, respectively, by measurements in a closed magnetic circuit and with an attached transducer.

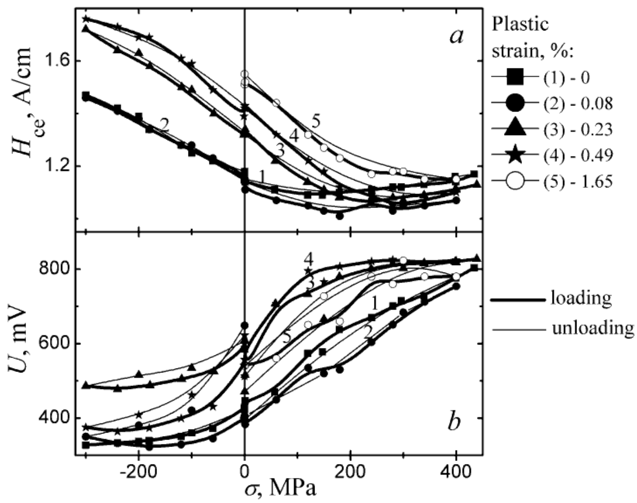

Fig. 5 Coercive force $H_{ce}(a)$ and rms voltage $U(b)$ measured by attached transducers as dependent on applied external stresses. The plastic strain values are 0 (1), 0.08% (2), 0.23% (3), 0.49% (4) and 1.65% (5).

It follows from figs. 4 and 5 that, at applied elastic stresses ranging approximately between -200 MPa and 120 MPa, the magnetic characteristics of all the specimens plastically pre-strained to different amounts vary monotonically and thus can be used to test working elastic stresses.

3.3 The effect of hydrogen sulphide on the magnetic parameters of the 12GB steel under uniaxial elastic-plastic tension

The values of ultimate strength σ_u, yield stress σ_y, percentage elongation at fracture δ, contraction ratio ψ and the magnetic characteristics of the steel under study in the initial state and after holding in hydrogen sulphide containing environment are given in the table. Here, $h_c^{0.4}$ and $h_c^{0.05}$ are coercive force values on minor hysteresis loops at a maximum magnetic induction of 0.4 and 0.05 T respectively. The values shown in the table are averaged experimental data for three specimens of each set. The deviations of individual characteristics from the mean values do not exceed 5%.

Table. The mechanical and magnetic properties of the 12GB pipe steel.

Duration of holding in H_2S, h	σ_u, MPa	σ_y, MPa	δ, %	ψ, %	H_c, A/cm	B_r, T	μ_{max}	$h_c^{0.4}$, A/cm	$h_c^{0.05}$, A/cm
0	474	374	23	77	3.81	1.47	1485	3.18	0.60
96	458	361	22	76	3.70	1.47	1496	2.86	0.58
192	498	426	14	70	3.95	1.52	1446	3.16	0.63
384	500	437	12	74	4.05	1.51	1515	3.19	0.71

Figure 6 shows stress-strain diagrams and strain (ε) dependences of the magnetic parameters of the specimens for specimens with mechanical and magnetic characteristics closest to the mean values. For the other specimens, the stress-strain diagrams and the strain dependences of the magnetic characteristics are similar to those shown in fig. 6. It follows from the table and fig. 6 that the 96-hour holding has little effect on the mechanical properties. At the same time, an increase in holding in a hydrogen sulphide containing media to 384 hours is accompanied by some increase in the strength characteristics and an almost twofold decrease in percentage elongation at fracture; it also results in numerical differences on the dependences $H_c(\varepsilon)$ and $h_c^{0.4}(\varepsilon)$ in the region of high strains; namely, the longer the holding in H_2S, the higher lie the curves corresponding to these dependences.

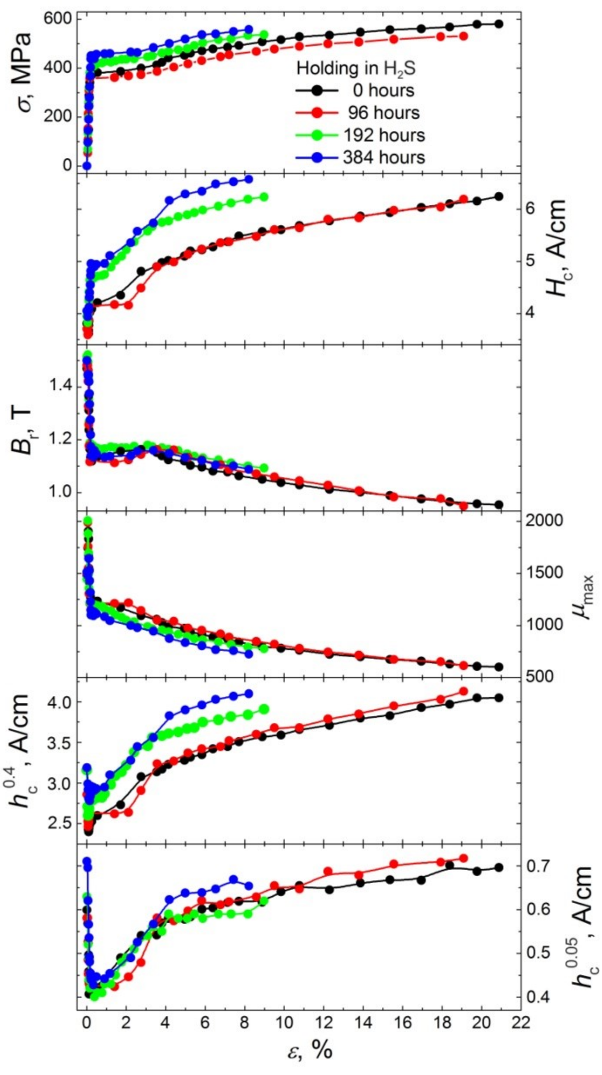

Fig. 6. Stress-elongation diagrams and elongation dependences of magnetic characteristics for the 12GB pipe steel specimens.

The action exerted by a hydrogen sulphide containing medium on the 12GB steel for

 https://doi.org/10.1051/matecconf/201814505003

96 hours has practically no effect on magnetic characteristics. The parameters H_c and $h_c^{0.05}$ are seen to tend to increase with the duration of holding in hydrogen sulphide.

As with the carbon steels St3 and 45 [14], for the alloy steel 12GB, except in the initial stage of loading, the strain dependences of the coercive force are qualitatively similar to the stress-strain diagrams, whereas the dependences of maximum magnetic permeability and residual induction are inverse. In the initial portion of the tension diagram (see fig. 7) the values of the coercive force slightly decrease and then increase. The nonmonotonic behaviour of the coercive force as a function of elastic strain is explainable by the appearance of a magnetic texture due to a positive magnetoelastic effect.

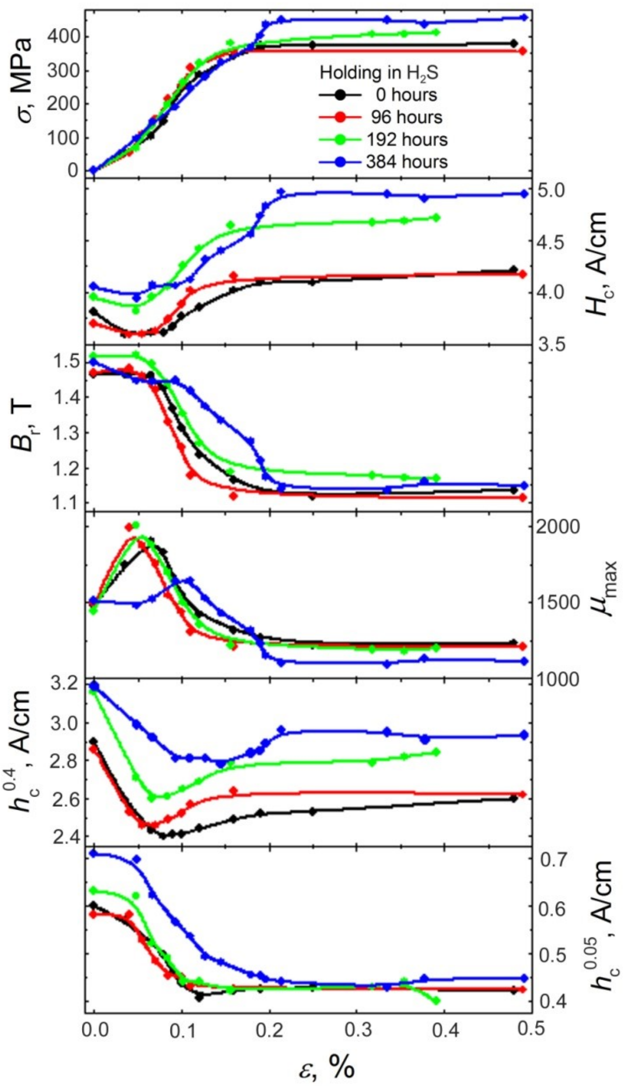

Fig. 7. The initial portions of loading diagrams for the 12GB steel specimens and the strain dependences of the magnetic characteristics of the steel.

Figure 8 shows coercive force, residual induction and maximum magnetic permeability as dependent on the magnitude of tensile stresses σ in relative coordinates. The magnetic characteristics are normalized to their values measured at $\sigma = 0$, the stresses being normalized to yield stress σ_y. As is obvious, the dependences $B_r(\sigma)$ and $h_c^{0.05}(\sigma)$ are unique in the practically important region of elastic stresses; namely, when the stresses grow from 0 to σ_y, the values of $h_c^{0.05}$ decrease by 30 to 40%, and the values of B_r decrease approximately by 30%, residual induction remaining practically unchanged in the initial stage of loading, when $\sigma < 100$ MPa. Thus, the value of the coercive force measured under magnetization reversal in weak fields can be used as a parameter for the evaluation of elastic strains in the 12GB pipe steel under conditions including the action of a hydrogen sulphide containing medium. Besides, it is obvious from fig. 8 that the minimum values of $h_c^{0.05}$ correspond to the yield stress of the specimens. In this connection, the value of $h_c^{0.05}$ can be used as a parameter for the evaluation yield stress for the 12GB steel.

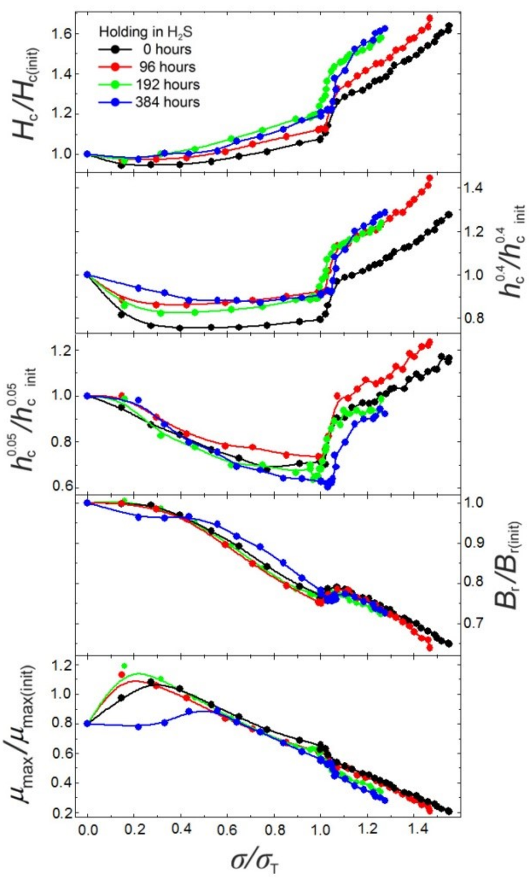

Fig. 8. Magnetic characteristics of the 12GB pipe steel as dependent on applied tensile stresses in relative coordinates.

4 Conclusion

It has been revealed that the behaviour of the magnetic characteristics of the steel (coercive force, residual induction and maximum magnetic permeability) with increasing plastic strain is monotonic. Therefore, these parameters or their combination can be used to evaluate the strain state resulting from pipe making, transportation and installation.

Due to residual stresses induced by plastic strain, the prehistory in the form of plastic strain affects the magnetic behaviour of the material during its subsequent elastic deformation, and this necessitates considering the initial stress-strain state of a metallic structure when developing magnetic techniques for the determination of its stress-strain parameters in operation.

For the steel studied, the range of elastic stresses (between -200 and 120 MPa) has been determined where the magnetic characteristics measured in the longitudinal direction vary uniquely and hence are usable for the evaluation of working elastic stresses.

The 96-hour action of H_2S has practically no effect on the mechanical and magnetic characteristics of the 12GB pipe steel. A longer holding in hydrogen sulphide causes notably lower plasticity, higher values of ultimate strength and yield stress and slightly increased coercive force.

The strain dependences of ultimate coercive force are qualitatively similar to the stress-strain diagrams for the 12GB steel, whereas those of maximum magnetic permeability and residual induction are inverse, except in the initial portion of loading, where the action of induced magnetoelastic anisotropy is evident.

In the stage of elastic strain of the 12GB steel, both in the initial state and after holding in hydrogen sulphide, a unique correlation was found between the coercive force measured on a minor magnetic hysteresis loop in weak fields and tensile stresses, and this enables this parameter to be used for the evaluation of elastic stresses in products made of the 12GB pipe steel. The minimum on the dependence $h_c^{0.05}(\sigma)$ corresponds to the yield stress of this steel both in the initial state and after holding in hydrogen sulphide.

In this study, to measure the magnetic and mechanical characteristics, we used the equipment of the Plastometriya collective use center affiliated to IES UB RAS. The study was partially supported by UB RAS project No 15-10-1-22.

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