The Effect of Hydrogen Sulphide on the Magnetic Behaviour of Tube Steel X42SS in Uniaxial Tension

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Abstract

Results of magnetic measurements made on 12GB tube steel samples (strength group X42SS) both in the initial state and after exposure to hydrogen sulphide within 96, 192 and 384 hours under uniaxial elastic-plastic tension are presented. 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 stresses, which enables his parameter to be used for estimating elastic stresses in products made of 12 GB tube steel under different conditions, including a hydrogen sulphide containing medium.

Keywords: Tube steel, Hydrogen sulphide, Uniaxial tension, Mechanical and magnetic properties

1. Introduction

The potentialities of magnetic nondestructive testing of the stress-strain state of ferromagnetic materials remain to be realized in full measure. This is largely due to the fact that in major works dealing with the effect of strains on the form of the hysteresis loop and with modelling the stress- and strain-dependences of magnetic properties the effect of stresses and strains on magnetic characteristics are studied under unloading, after the external stresses have been relieved[1-15]. However, components of different structures are, as a rule, operated under force actions; besides, the published research on the behaviour of magnetic characteristics of materials during deformation are fragmentary and often contradictory[16–17].

In oil and gas industry problems of estimating the degradation of the strength properties of tube steels are currently urgent, especially those operating in corrosion-active environments containing hydrogen. Since in hydrogen sulphide containing media intensive hydrogenation of metal takes place, which leads to pores filled with hydrogen in ductile steels and laminations (mainly along sulphide inclusion lines). In more brittle steels hydrogenation causes cracks.

Tube steel (Russian grade 12GB) intended for operation in “acid media” was studied (steel of the X42SS group according to the classification of American Oil Institute). Tubes made of steel of this type are used, e. g., for gas-gathering pipeline systems in Astrakhan gas-condensate field (the product transported contains up to 25 % hydrogen and up to 14 % carbon dioxide).

In order to develop non-destructive testing methods for this steel, the effect of hydrogen on magnetic properties was studied under conditions of elastic and plastic strains.

2. Test specimens and measurement procedure

Magnetic properties of test specimens cut out longitudinally from the wall of a tube Ø114×13 mm were studied under uniaxial tension. The test portions of the specimens were 80 mm long and 6×4 mm^2 in the cross section. The chemical composition of the specimens is given in table 1. Four sets of specimens were examined in the initial condition and under the action of hydrogen sulphide within 96, 192 and 384 hours.

Table 1. Chemical composition of the specimens, mass %

C	Si	Mn	Cr	Ni	Cu	Nb	V	Al	S	P	N	As
0.115	0.27	0.8	0.024	0.048	0.28	0.039	0.004	0.043	0.004	0.008	0.008	0.01

The specimens were saturated with hydrogen sulphide in the "A" model medium used in the NACE TM0177-2005 standard (5% NaCl solution + 0.5% CH_3COOH solution in distilled water saturated with hydrogen sulphide; H_2S content was 2400 to 3000 mg/l; pH = 3.4). The temperature kept in the bay was 20°C with an error of ±2°C, the pressure slightly exceeding atmospheric.

Magnetic measurements were made in a closed permeameter-type magnetic circuit with the aid of the Remagraph C500 hysteresisgraph. The magnetic field was applied along the specimen tension axis, the axis of the induction search coil being also parallel to the tension axis. The strength of the internal magnetic field H was measured by a C-shaped magnetic potentialmeter. The magnetic hysteresis loop at a maximal internal field of 60 kA/m was recorded on the "B-H" plane (B is magnetic induction) by memorizing 2500 points. The measuring error for the field and induction did not exceed ±3 %. The coercive force H_c and residual induction B_r was determined on the major hysteresis loops, and the coercive forces $h_c^{0.4}$ and $h_c^{0.05}$ were determined on minor ones at maximal magnetic induction 0.4 and 0.05 T, respectively. Besides, maximum magnetic permeability μ_{max} was determined by the normal magnetization curve.

Tension was performed at room temperature. The tests were conducted on a testing machine with a maximum force of 50 kN, with a velocity of the active clamp of 2 mm/min. The value of strain in the course of loading was determined by means of raster displacement transducers fastened directly to a specimen. The tests were performed with a small elongation step in the whole interval of the stress-strain diagram up to specimen fracture. At each step the process of loading was suspended once a certain amount of strain was attained, whereupon magnetic hysteresis loops were measured without load relief. After the measurements, the demagnetized specimen was again deformed in order to obtain the next measurement point. The specimen was demagnetized before and after each magnetic measurement.

3. Results and discussion

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 table 2. The values are shown in the table result from the averaging of experimental data for three specimens of each set. The deviations of individual characteristics from the mean values doe not exceed 5 %.

Figure 1 shows stress-elongation diagrams and the magnetic parameters of the specimens as dependent on percentage elongation ε for specimens with mechanical and magnetic characteristics closest to the mean values. For the other specimens, the stress-elongation diagrams and the strain-dependences of magnetic characteristics are similar to those shown in fig. 1. It follows from table 2 and fig. 1 that the 96-hour holding has little effect on the mechanical properties. At the same time, an increase of 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.

Table 2. The mechanical and magnetic properties of tube steel 12GB

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

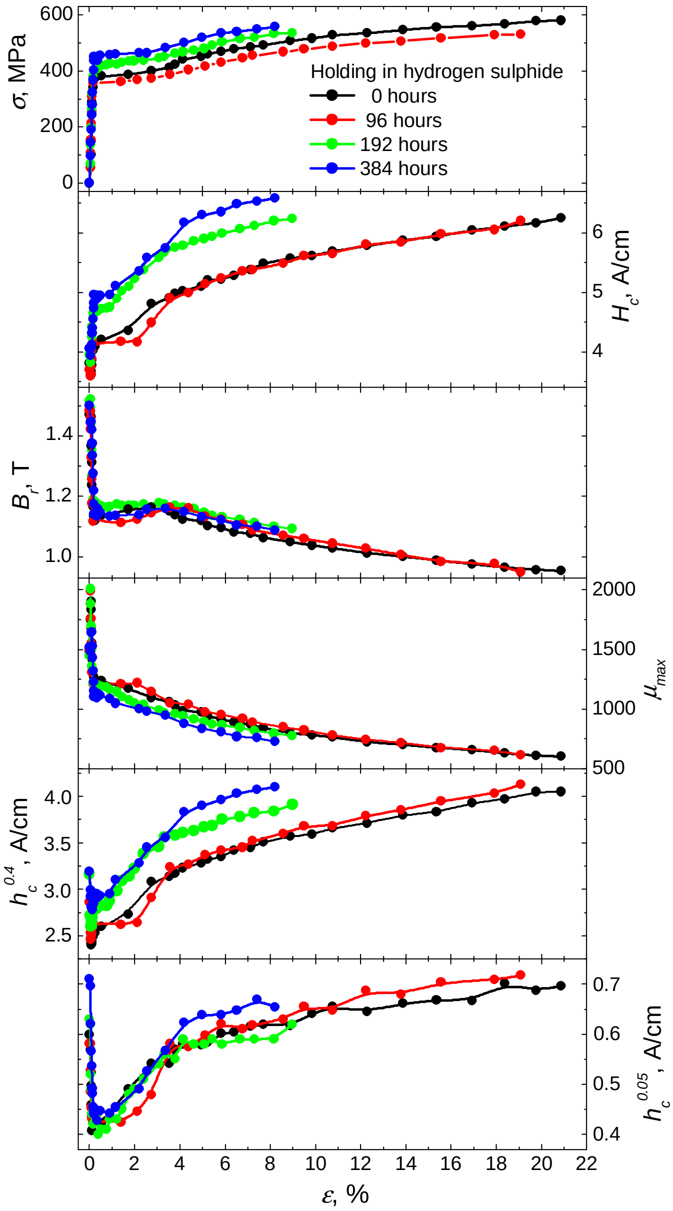

Fig.1. The stress-elongation diagrams and magnetic characteristics as dependent on the percentage elongation of specimens made of tube steel 12GB.

The action exerted by a hydrogen sulphide containing medium on steel 12GB within 96 hours has no effect on magnetic characteristics, see table 2. A longer holding gives some increase in the coercive force measured on minor hysteresis cycles.

As with carbon steels St3 and 45 [18], for 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. 2) the values of the coercive force in strong and moderate fields (H_c and $h_c^{0.4}$, respectively) somewhat 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[2] due to a positive magnetoelastic effect (magnetostriction and external stresses have the same sign). The magnetic moments are in this case oriented along the tension axis, and, when magnetization is directed along the tension axis, the coercive force decreases and magnetic permeability grows. However, as loading proceeds, the magnetostriction of the steel may change its sign[2], and this causes a negative magnetoelastic effect and changes the type of the magnetic texture. Besides, the "sign" of the magnetoelasic effect can be governed by the second constant of magnetostriction λ_{111}, which is negative in iron and iron-carbon alloy crystals. Affected by these factors, the coercive force will grow.

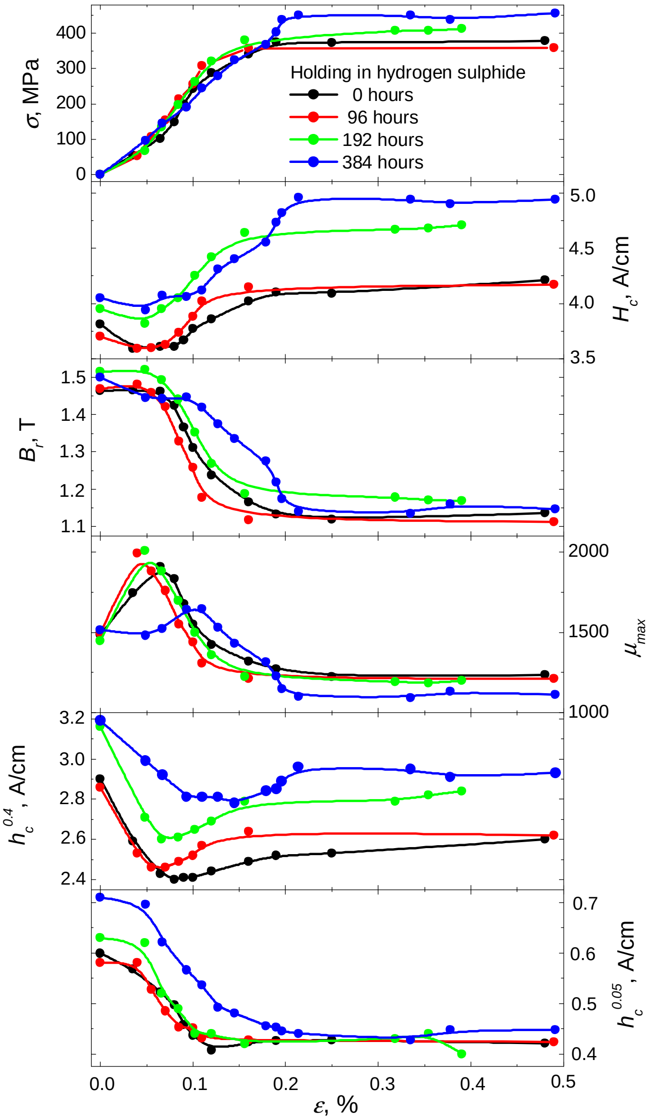

Fig.2. The initial portions of the loading diagrams for specimens made of steel 12GB and the strain-dependences of its magnetic characteristics.

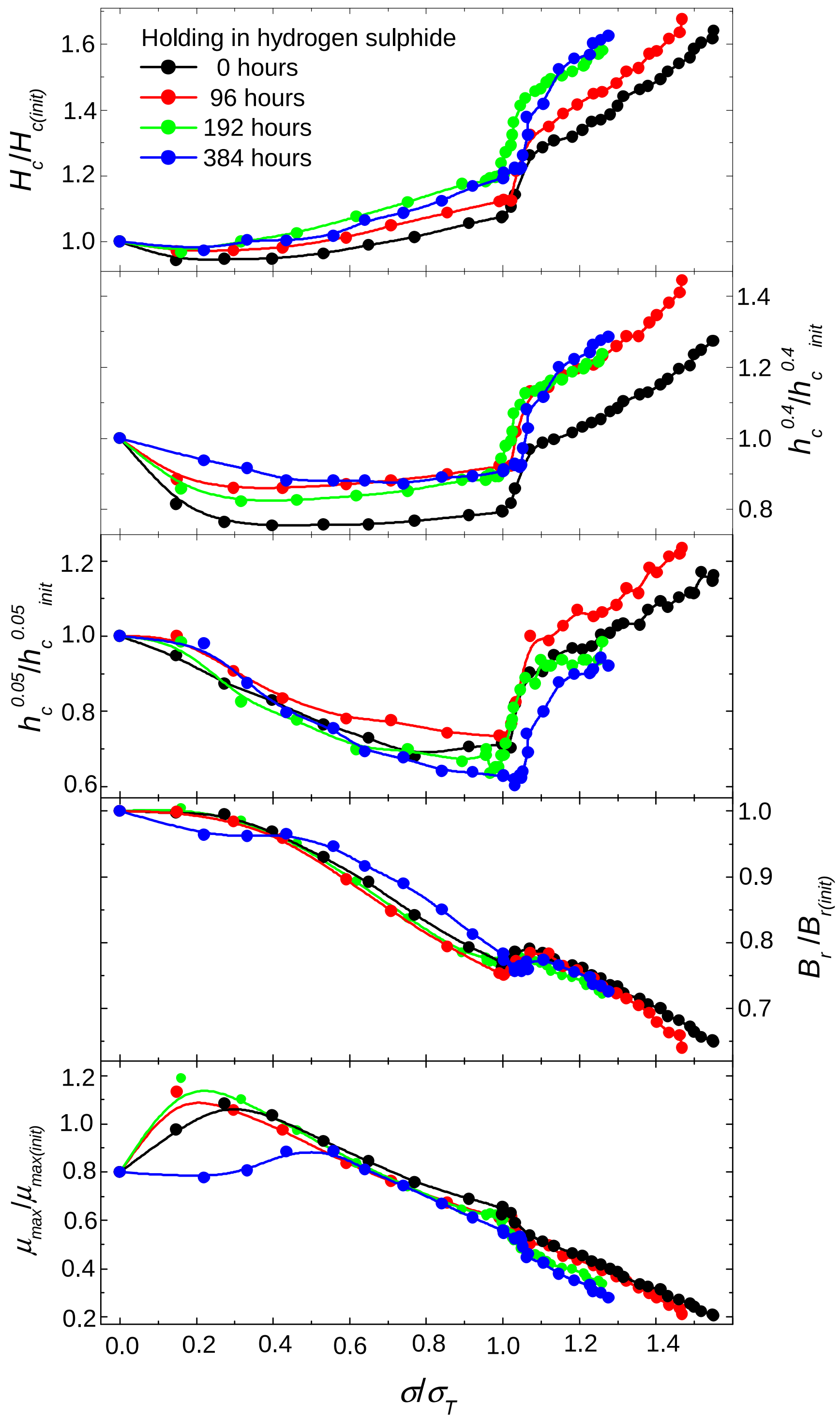

Fig.3. Magnetic characteristics of tube steel 12GB as dependent on applied tensile stresses in relative coordinates.

Figure 3 shows the 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, such magnetic characteristics as maximum magnetic permeability and the coercive force measured on the major hysteresis loop and under magnetization reversal in moderate fields vary nonmonotonically as elastic stresses grow. The dependences $B_r(\sigma)$ and $h_c^{0.05}(\sigma)$ are unique in the practically important region of elastic stresses: when the stresses grow from 0 to σ_y, the quantities $h_c^{0.05}$ decrease by 30 –

40%, and B_r decrease approximately by 30%, residual induction being practically unchangedin the initial stage of loading, when σ< 100 MPa.

Thus, figs. 2 and 3 indicate that the value of the coercive force measured under magnetization reversal in weak fields can be used as a parameter when estimating elastic strains in tube steel 12GB under conditions including the action of a hydrogen sulphide containing medium. On the σ-dependences of magnetic parameters there are inflections at stresses approximately corresponding to the initial and final stresses of the yield plateau (respectively, σ_y and $\approx 1.1\sigma_y$) for the specimens studied both after the action of hydrogen sulphide and in the initial state. The intensity of variation in the magnetic characteristics in this stress interval is much higher. The variation of the values of residual induction and maximum magnetic permeability is about 5 %, and that of the value of the coercive force is 20 – 40 %. The values of H_c and $h_c^{0.4}$ increase with stresses both in the region of elastic strains and under plastic strain, and it is only the intensity of the growth of H_c and $h_c^{0.4}$ that increases with the advent of the stage of developed plastic strain. On the dependences $h_c^{0.05}(\sigma)$ there are minimums – the value of $h_c^{0.05}$ in the elastic strain region decreases as stresses increase, and it increases in the stage of developed plastic strain. As is obvious from Fig. 3, in all the instances studied, the yield stress is in keeping with the minimal values of $h_c^{0.05}$. In this connection, the quantity $h_c^{0.05}$ is the most preferable as a parameter for evaluating the yield stress of steel 12GB by magnetic measurements.

4. Conclusion

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

The strain-dependences of ultimate coercive force are qualitatively similar to the stress-strain diagrams foe steel 12GB, 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. A longer action of a hydrogen sulphide containing medium leads to a numerical difference on the dependences $H_c(\varepsilon)$ and $h_c^{0.4}(\varepsilon)$ in the region of high strains, namely, the longer the duration of holding in H_2S, the higher lie the curves with respect to the initial state.

In the stage of elastic strain of steel 12GB, 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 the tensile stresses, and this enables this parameter to be used for estimating elastic stresses in articles made of tube steel 12GB. The minimum on the dependence $h_c^{0.05}(\sigma)$ corresponds to the attainment of the value of yield stress for this steel.

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References

[1] Villary E., Ann. Phys. Chem., 1865, Number 126, p87.
[2] Vonsovsky S.V., Shur Ya.S., Ferromagnetism, M.-L., OGIZ, 1948, 816p.
[3] Bozorth R.M., Ferromagnetism, Van Nostrand, New York, 1951, p600-609.
[4] Babich B.K., Pirogov V.A., On the nature of the coercive force variation in the deformation of annealed carbon steels, FMM, 1969, Volume 28, Number 3, p447-453.
[5] Atherton D.L., Jiles D.C., Effects of stress on magnetization, NDT International, 1986,

Volume 19, Number 1, p15-19.
[6] Jiles D.C., The effect of compressive plastic deformation on the magnetic properties of AISI 4130 steels with various microstructures, J. Phys. D., Appl. Phys., 1988, Number 21, p1196-1204.
[7] Thompson S.M., Tanner B.K,. The magnetic properties of specially prepared pearlitic steels of various carbon content as a function of plastic deformation, J. Magn. Magn. Mater., 1994, Number 132, p71-88.
[8] Bulte D.P., Langman R. A., Origines of the magnetomechanical effect, J. Magn. Magn. Mater, 2002, Volume 251, Number 2, p229-243.
[9] Langman R. A., Magnetic properties of mild steel under conditions of biaxial stress, IEEE Trans. Magn, 1990, Volume 26, Number 4, p1246-1251.
[10] Sablik M.J., Kwun H., Burkhardt G.L., Biaxial stress effects on hysteresis, J. Magn. Magn. Mater, 1995, Volumes 140-144, p1871-1872.
[11] Jayakumar T., Vaidyanathan S., Raj B. et al., Effect of tensile deformation on micromagnetic parameters in 0.2% carbon steel and 2.25Cr-1Mo steel, Acta Mater, 1999, Volume 47, Number 6, p1869-1878.
[12] Sablik M.J., Modeling stress dependence of magnetic properties for NDE of steels, Nondestr. Test. Eval., 1989, Volume 5, p49-65.
[13] Jiles D.C., Devine M. K., The law of approach as a means of modelling the magnetomechanical effect, J. Magn. Magn. Mater, 1995, Volumes 140-144, p1881-1882.
[14] Sablik M.J., Jiles D.C., Wohlfarth computational model for hysteretic magnetic properties in a ferromagnetic composite rod under torsion, Journal of Physics D: Applied Physics, 1999, Volume 32, p1971-1983.
[15] Sablik M.J., Yonamine T., Landgraf F., Modeling plastic deformation effects in steel on hysteresis loops with the same maximum flux density, IEEE Trans. Magn., 2004, Volume 40, Number 5, p3219-3226.
[16] Makar J.M., Tanner B.K., The in situ measurement of the effect of plastic deformation on the magnetic properties of steel, Part I, Hysteresis loops and magnetostriction, J. Magn. Magn. Mater., 1998, Volume 184, p193-208.
[17] Makar J.M., Tanner B.K., The in situ measurement of the effect of plastic deformation on the magnetic properties of steel, Part II, Permeability curves, J. Magn. Magn. Mater., 1998, Volume 187, p353-365.
[18] Gorkunov E.S., Zadvorkin S.M., Smirnov S.V., Mitropolskaya S.Yu., Vichuzhanin D.I., Correlation between the stress-strain parameters and magnetic charakteristics of carbon steels, FMM, 2007, Volume 103, Number 3, p322-327.