Effect of texture on mechanical and magnetic properties of steel from the petroleum distillation column

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Abstract

Texture, mechanical properties and coercive force of steel 09G2S from the column fragment of petroleum distillation after prolonged use studied. Anisotropy of mechanical properties and coercive force take place. Significant pair wise linear correlations and appropriate regression equations with coefficients reliability of approximation not less than 0.90 were found between magnitudes of the coercive force, tensile strength, yield strength, elongation and texture characteristics. Found correlations may be used for nondestructive mechanical properties control of investigated steel by means of monitoring of coercive force.

Keywords:

texture,
anisotropy,
mechanical properties,
coercive force,
correlation

1 Introduction

Low alloy steels of type A515 and A516 are widely used in equipment of refinery complex, in particular for the production of distillation petroleum columns [1]. During the exploitation of the above equipment arise problems of mechanical properties of steel control, as well as the further safe operation estimation. Uniaxial tensile tests, fatigue, experiments on the long-term strength, etc. are carried out to study the mechanical properties [2, 3]. Cutting of samples from appropriate plots of material is necessary for such research. This requires stopping of the equipment operation. Therefore the development of non-destructive monitoring methods of the structural state and properties of the steel is important. The method of coercive force measuring is one of perspective non-destructive monitoring methods of structural condition of steels. Crystallographic texture as well as shape and size of grains, and elastic stresses have a main influence on the coercive force and her anisotropy [4]. Possibility of the structural state evaluation, of accumulated fatigue damage level, value of internal stress by measurement of coercive force was demonstrated in number of studies (e.g., [5-8]). In [6] was found a linear correlation of coercive force with the pole density on inverse pole figures (IPF) as well as with broadening of appropriate X-ray diffraction lines with increasing of the hydraulic pressure in the steel pipeline at testing. However relationship of coercive force (H_C) anisotropy with mechanical and structural characteristics of ferromagnetic construction steels is studied deficiently.

This work aimed to ascertainment of reasons anisotropy coercive force measured by non-destructive method, as well as relationship of coercive force with texture and mechanical characteristics of low-alloy steel of petroleum distillation column after long-term use.

2 Experimental material and methods

Low alloy steel of type 09G2S thickness of 20 mm from the column fragment of petroleum distillation after long-term use was by material for the study. The studied steel has the following chemical composition: 0.11 wt% C; 1.47 Mn; 0.70 Si; 0.13 Cr; 0.05 Ni; 0.06 V; 0.02 A1; 0.02 P; 0.009 S; 0.05 Cu; 0.04 Nb; 0.03 wt% Mo; Fe balance.

The coercive force H_C was measured non-destructively using a magnetic analyzer (coercimeter) KRM-Ts-MA by overlay of pole tips of the portable measuring device on surface of the test product. The area of the test products between the pole tips of the magnetic converter is periodically magnetized to saturation by current pulses with amplitude of at least 2 A. Automatic compensation of residual magnetization field is then carried out. Value of coercive force is automatically calculated by the current magnitude of magnetic field compensation. Readings of device are dependent only from the metal properties but independent of confounding factors such as the protective coating (paint, film, etc.) to 6 mm on controlled metal or equivalent to this gap the corrosion metal, roughness, curvature etc. The maximum error does not exceed 2%. [13]. Coercive force was measured through every 15° from longitudinal direction (LD) up to the transverse direction (TD) orienting the measuring probe without damaging the product.

Samples for mechanical testing by uniaxial tension (Figure 1) with the diameter of working part of 3 mm were cut from the column fragment through every 15° from longitudinal direction (LD) up to the transverse direction (TD).

FIGURE 1 Sample after the test

The arithmetic average of test results of at least three specimens in every of above directions has been taken as the value of the corresponding mechanical characteristics. Mechanical testing was performed on a setup 1246-R. Velocity of the active grip was 2 mm / min. Mechanical properties were determined according to standard procedures [10].

The X-ray method was used for the study of texture [11]. Scanning θ-2θ of the sample without texture (which was manufactured from sawdust of investigated steel after recrystallization), as well as of specimens cut out in the ND, DD, and in TD was performed by means X-ray diffractometer DRON-3M by Bragg-Brentano geometry in the radiation of Kα - Mo. Texture was investigated in the ND near the outer convex surface of the column, in the middle of fragment thickness, and near of her inner concave surface. Appropriate surfaces were chemically polished up to 0.1 mm before recording for removing of layer distorted by machining. On obtained data were constructed IPF for respective directions described above. The three-dimensional distribution function of the crystals orientation in space of ideal orientations were calculated by us from the IPF LD and the IPF TD according to the method described in earlier our work [12].

Metallographic structure of end surfaces of samples orthogonal to the RD and TD was examined by the microscope Axioplan 2 of firm KARL ZEISS.

3 Results and Discussions

Results of mechanical tests and measurement of the coercive force H_c are shown in Table 1.

TABLE 1 Mechanical properties and coercive force of steel samples, cut out in different directions from the fragment of distillation petroleum column

Angle with the LD, °	Tensile strength σ_m, MPa	Conditional yield strength $\sigma_{0.2}$, MPa	Relative elongation, $\varepsilon = \Delta l / l$, %	Coercive force, H_c, A/cm
0	400±2.0	255±1.4	31.0±0.4	5.9±0.12
15	405±2.2	258±1.8	30.2±0.4	6.1±0.12
30	416±2.3	265±2.1	28.8±0.4	6.3±0.12
45	425±2.2	272±2.3	28.0±0.4	6.5±0.12
60	421±2.0	268±2.0	28.4±0.4	6.5±0.12
75	417±2.0	266±1.5	29.4±0.4	6.4±0.12
90	415±1.8	260±2.5	30.0±0.4	6.2±0.12

Anisotropy of mechanical characteristics and coercive force take place. The minimal values of the strength properties of σ_m, $\sigma_{0.2}$, and the coercive force H_c are observed in the LD. Their maximal values occur in the LD+45°, and in the TD they take an intermediate value. Elongation ε shows the opposite behavior.

Anisotropy coefficient η was calculated by the formula

$$\eta = \left(F_{max} - F_{min} / F_{min}\right) \cdot 100\% . \quad (1)$$

Here $F_{\max}$ and $F_{\min}$ are maximal and minimal values of the corresponding property.

Anisotropy coefficients of σ_m, $\sigma_{0.2}$, H_c and ε amounted respectively 6.25 %, 6.27 %, 10.71 % and 10.17 %.

Strong linear correlations of the H_c value with values of mechanical characteristics σ_m, $\sigma_{0.2}$ and ε take place. Corresponding regression equations with high reliability approximation coefficients R^2 have the form

$$\sigma_m = 38.2 H_c + 174.8 ;\ R^2 = 0.92, \quad (2)$$

$$\sigma_{0.2} = 26.1 H_c + 99.6 ;\ R^2 = 0.93, \quad (3)$$

$$\varepsilon = -4.6 H_c + 58.0 ;\ R^2 = 0.89. \quad (4)$$

Experimental inverse pole figures obtained by us are presented in Figure 2.

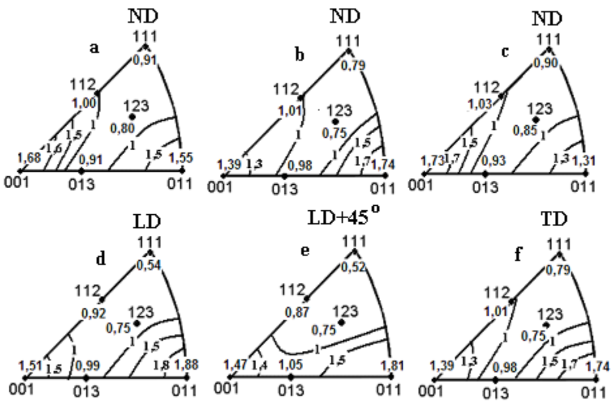

FIGURE 2 IPF's of steel column: a, c correspond to the convex and concave surface of the column respectively; b corresponds to the middle of the thickness of the metal; d-f correspond to the LD, LD+45° and TD

Texture of polycrystalline bodies presents a continuous distribution of crystals by orientations. At the same time there are certain preferable orientations of crystals, which are for clarity usually described using ideal orientations. Important components of the low carbon steel rolling texture are arranged along three fibres orientations [11]:

1) α-fiber with the fiber axis <110> parallel to the rolling direction including the main components of {001} <110>, {112} <110> and {111} <110>.

2) γ-fiber with the fiber axis <111> parallel to the normal direction including the main components of {111} <110> and {111} <112>.

3) ε-fiber with the fiber axis <110> parallel to the transverse direction including the main components of {001}

<110>, {111} <112>, {554} <225> and {011} <100>.

When referring to ideal orientations {hkl} <uvw> in the cylindrical sample we mean that planes of family {hkl} are located in a plane tangent to the cylindrical surface, and a set of crystallographic directions <uvw>, owned by {hkl}, are parallel to cylinder axis.

From Figure 2 it can be concluded that parallel to the side surface of the column metal are arranged families of crystallographic planes {001} and {110} since their pole density is greater than 1 that corresponds to the state without texture. Crystallographic directions <110> and <100> of families mainly coincide with the LD, TD and LD + 45°. A three-dimensional ODF was calculated by us in the space of ideal orientations on the base of IPF LD (Figure 2(b)) and IPF RD (Figure 2(d)). Texture can be described as a combination of ideal orientations with the volume content, which are presented in the Table 2 as it was determined by the analysis of the ODF.

Effect of crystals orientation on the coercive force electrical steel previously is investigated in several studies [e.g. 14, 15]. Summarizing, can be concluded that the anisotropy of coercive force in the steel dependent not only from crystal orientation (i.e. from texture) but and from features of the magnetic domains formation.

TABLE 2 The composition and volume content of ideal orientations in the texture of steel of distillation oil column

Ideal orientation	{100}<010>	{100} <011>	{100} <013>	{110} <110>	{110} <111>	{110} <001>
Volume content	0.20	0.12	0.11	0.18	0.14	0.25

Crystallographic texture, shape and size of the grains, and the elastic stresses have a mainly influence on the coercive force and its anisotropy [4] as mentioned above. Metallographic analysis showed that the investigated steel has a typical ferrite – pearlite microstructure with average grain size of 22 μm (Figure 3). This microstructure can hardly be the main cause of the anisotropy of the coercive force.

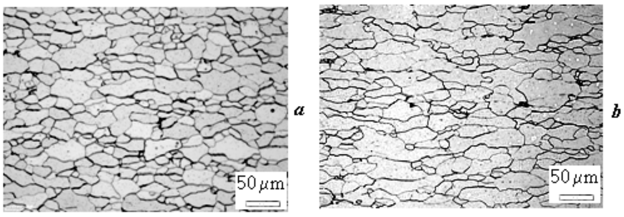

FIGURE 2 Ferrite – pearlite structure of the investigated steel: ***a***, ***b*** have been photographed from the LD and TD direction

These features are caused by the magnitude of the external magnetizing field, if the steel does not magnetized to saturation. But when the coercive force is measured using the coercimeter, steel is magnetized to saturation, since the magnetizing field is sufficiently large (B = 1.5 T) [13]. Therefore, we can assume that the behaviors of domains in the magnetization and demagnetization play a secondary role in formation of the coercive force anisotropy, but the main role belongs to the energy of the magnetic crystallographic anisotropy in the investigated steel.

Let's estimate the energy of the magnetic crystallographic anisotropy in the investigated material. Suppose that the coercive force is associated only with the energy of the magnetic crystallographic anisotropy (external applied mechanical stresses are absent, structure of the investigated steel is homogeneous). Energy of the magnetic crystallographic anisotropy as a first approximation is expressed by the following equation [4] for the material with cubic lattice

$$W_k \approx K_1\left(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_1^2\alpha_3^2\right), \tag{5}$$

Here α_1 , α_2 and α_3 are direction cosines of the magnetization with respect to the cube axes; K_1 is anisotropy constant.

Let's will call of function energy of magneto-crystalline anisotropy the expression

$$\psi=\left(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_1^2\alpha_3^2\right). \tag{6}$$

The direction cosines of orientations indicated in Table 2 are presented in Table 3. Numerical values of the function Ψ of magnetic crystallographic anisotropy energy calculated from (3) for combinations of ideal orientations as well as corresponding volume content (Table 2) and considering direction cosines (Table 3) are shown in Table 4.

TABLE 3 Ideal orientations and functions of the magnetic crystallographic anisotropy energy

α_1	α_2	α_3
cosφ	sinφ·sin90º	sinφ·cos90°
cos(φ+45º)	sin(φ+45º)·sin 90°	sin(φ+45º)·cos90º
cos(φ+18.43º)	sin(φ+18.43º)·sin90º	sin(φ+18.43º)·cos90º
cos(φ+90º)	sin(φ+90º)·sin45º	sin(φ+90º)·cos45º
cos(φ+54.7º)	sin(φ+54.7º)·sin 45º	sin(φ+54.7º)·cos45º
cos φ	sinφ·sin 45º	sinφ·cos45º

TABLE 4 The calculated numerical values of function Ψ of the magnetic crystallographic anisotropy energy

Angle with LD,º	0	15	30	45	60	75	90
Ψ	0.09	0.16	0,21	0.24	0.23	0.19	0.15

Function Ψ takes the maximal value in the direction of LD + 45º. The minimal value of Ψ is observed in the LD. Function Ψ has an intermediate value in the TD. This is consistent with the character of coercive force anisotropy (Table 1). A strong linear correlation between the values of Ψ function and H takes place, as showed the correlative analysis conducted by us. The corresponding regression equation with a coefficient of reliability correlation R^2 = 0.91 has the form

$$\Psi = 0.23H_C - 1.23. \tag{6}$$

Thus, the character of the observable coercive force anisotropy in the studied steel of the oil distillation column can be explained, mainly by influence of the magnetic crystallographic anisotropy energy. Correlations (2) - (4) can be used to non destructive control the mechanical characteristics of steel 09G2S by measure of the coercive force during operation of oil distillation column.

4 Conclusion

(1) Mechanical properties, the coercive force, and the texture in the fragment of steel petroleum distillation column after prolonged use studied.

(2) Anisotropy of mechanical properties and coercive force take place. Minimal values of strength properties σ_m and $\sigma_{0.2}$ coercive force H_c are observed in the longitudinal direction, their maximum values occur in a diagonal direction, and in the transverse direction abovementioned properties takes the intermediate values. Elongation ε shows the opposite behavior.

(3) Strong linear correlations of the coercive force H_c with mechanical characteristics tensile strength σ_m, proof strength $\sigma_{0.2}$, and elongation ε are found. Reliability coefficients of linear approximations were no less than 0.89.

(4) Energy of the magnetic crystallographic anisotropy that is associated with orientation of crystals (i.e. with the texture), is main factor of coercive force anisotropy in the investigated steel. A strong linear correlation (with a correlation coefficient of at least 0.9) was found between calculated values function of magnetic crystallographic anisotropy energy and experimental values of coercive force.

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