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NONDESTRUCTIVE EVALUATION OF FERROMAGNETIC STEEL STRUCTURES AND COMPONENTS BY COERCIVE FORCE MEASUREMENTS

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1. INTRODUCTION

The nondestructive evaluation (NDE) techniques based on the measurements of magnetic parameter (coercive force, remanence, initial permeability, etc.) are reasonably effective for evaluating the structural–phase and stressed–strained states of ferromagnetic steels, because the magnetization processes in ferromagnetic materials are closely related to the microstructure and the type (tensile or compressive) and the value of applied or residual stresses in the inspected materials. Mechanical properties of steel such as hardness, strength, ductility and strain hardening are structure-sensitive properties related to the microstructure, composition, and fabrication methods. Magnetic properties are sensitive to the same chemical, microstructure and processing conditions. Therefore, in many cases measurements of magnetic properties can ensure the estimation of the mechanical properties of ferromagnetic steels possible to serve for NDE for structural integrity assessment [1–14].

At present, among known magnetic characteristics, only the coercive force has been widely applied for the inspection of the structures of ferromagnetic steel. Other magnetic parameters that can be proposed to solve a wide range of problems of structure and component evaluation are not widespread in NDE practice.

In this paper different tools for coercive force measurement and the investigations concerned with new original applications are presented.

First investigated application is related to the steam pipelines of power plants operated under high pressure (up to 16 MPa) and elevated temperatures (up to 570º C). The results obtained are important for prediction of the steam pipelines residual life by the evaluation of the structural-mechanical states of the steam pipelines steels after long-term operation by measuring their coercive force.

Second application is concerned with the estimation of stresses by the measurements of the coercive force distribution along ship load-bearing elements during operational loading. The measurements were done on the hatch coamings of the “river-sea” cargo ship. It was shown that areas of highest coercive force (and mechanical stresses) are not in compliance with the recommendations of the International Maritime Organization concerned the strain gauge placement. New strategy for ship construction monitoring based on the coercive force measurements in the preliminary determined critical zones was proposed.

Third application is related with the coercive force of comparatively small details magnetized in open magnetic circuit (solenoid). Special solenoid and device applied for this application as well as some inspection results obtained for the components fabricated from tungsten-cobalt hard alloys are presented.

2. INSTRUMENTATION FOR MAGNETIC PARAMETERS EVALUATION

2.1. Instrumentation for magnetic parameters evaluation in closed circuit

Local measurements of magnetic parameters for large-area structures are most frequently performed using attachable (surface) probes. Coercimeters (coercive force meters) and magnetic multiparameter structuroscopes (magnetic analyzers) with U-shaped electromagnet with a magnetic-flux sensor, which is built into it, usually serves as the measuring transducer. Magnetic-flux sensor (for example, Hall sensor) can be placed in the electromagnet gap or located near the magnetic core to register the leakage flux, can be used in different designs. In most cases, the value of the magnetic field in an inspected object is estimated by the value of the magnetizing current in the electromagnet windings.

2.1.1. Instrument for single parameter evaluation

Magnetic structurescope (coercimeter) KRM-Ts (fig. 1) is developed by Ukrainian company Special Scientific Engineering for local measurements of coercive force in closed magnetic circuit by attachable (surface) type probes (fig. 2) [8, 12–14]. Coercive force measurements can be performed directly on operated equipment at temperature of the metal from -40 up to 600º C through the dielectric coating up to 6 mm. Main technical data: range of coercive force measurement, A/cm 1 – 40; error of the measurements from 5 % to 2,5 %; time of measurement cycle, sec, at most - 8; time of continuous operation without recharging, hour, at least – 8.

Fig. 1. Magnetic structurescope (coercimeter) KRM-Ts with calibration blocks.

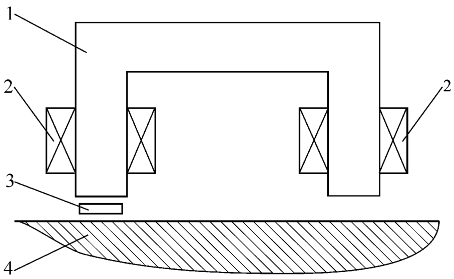

Fig. 2. Attachable (surface) type probes for local coercive force measurements:
1 – U-shaped magnetic core,
2 – magnetizing windings,
3 – Hall-type magnetic flux sensor:
4 – inspected object.

Coercimeter KRM-Ts can be supplied with attachable type magnetic probes of different size (Fig. 3).

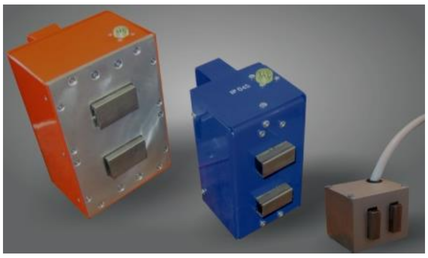

Fig. 3. Different size attachable type magnetic probes.

2.1.2 Instrument for multiparameter magnetic evaluation of material structures

Magnetic analyzer MA-05 (fig. 4) is developed for measurement of at least six parameters of hysteresis loop: coercive force, residual induction, magnetic conductivity, loop area and relaxation parameters. These parameters are automatically converted into physical characteristics according to given equations.

Fig. 4. Magnetic analyzer MA-05 for multiparameter measurements.

As result of evaluation the shape and area of the magnetic hysteresis loop and the main parameters used to describe this loop (in particular, the coercive force H_C) are presented on the PC screen (fig. 5). The designs and parameters of the attachable type magnetic probes are same as on fig. 2 and 3.

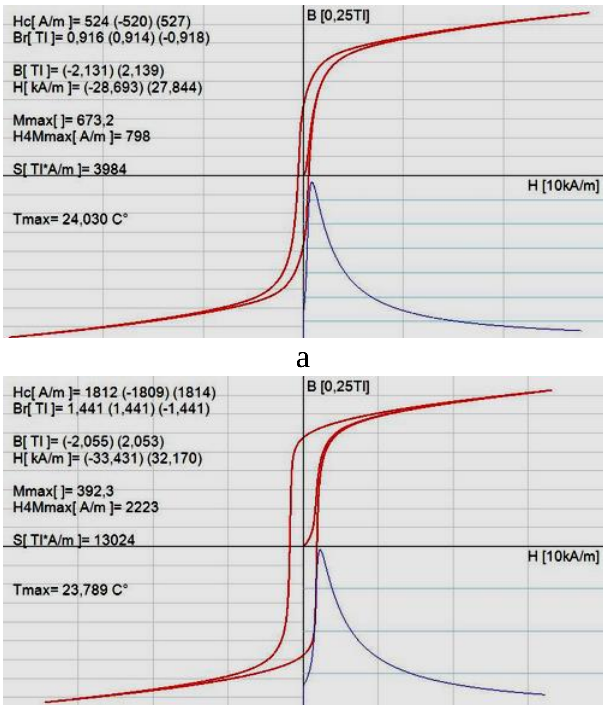

Fig. 5. Final results presentations obtained for evaluated steel with coercive force 524 A/m (a) and 1812 A/m (b).

2.1.3. Instrument for coercive force measurement in open magnetic circuit

For evaluation of small size details in open magnetic circuit the VKS-968 type coercimeter (fig. 6) was developed in Karpenko Physical-Mechanical Institute of NAS of Ukraine [8, 9].

VKS-968 type coercimeter is intended for the integral coercive force measurement of comparatively small specimens and products produced from sintering hard alloys (tungsten, titanium-tungsten and titanium-tantalum-tungsten groups) in compliance with the state standard GOST 3882-74 (ISO 513-75) requirements. This gage realizes the method of coercive force measurements in an open magnetizing circuit comply with the state standard GOST 24916-81 (ISO 3326-75) (fig. 7).

Fig. 6. VKS-968 type structurescope (coercimeter) for coercive force evaluation in open magnetic circuit: magnetizing-demagnetizing unit (left); measuring unit (right).

Coercive force is determined by the current in the demagnetizing coil in moment, when magnetization of testing object becomes equal to the zero [9]. All operations are realized automatically. There are two units: measuring and magnetizing-demagnetizing (Fig. 6). Measuring unit provides the functions of control, measuring and presentation of the results obtained on digital display. Magnetizing-demagnetizing unit contains magnetizing and demagnetizing solenoids and flux-gate gradiometer as a sensor of inspected object magnetization (Fig. 7).

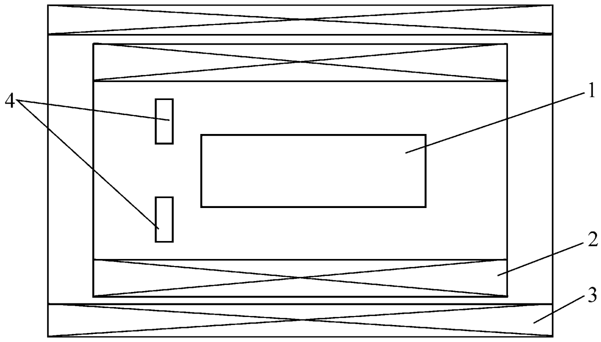

Fig. 7. The principle of coercive force measurement in open magnetic circuit:
1 – testing object, 2 – magnetizing coil (solenoid), 3 – demagnetizing coil (solenoid), 4 – flux-gate gradiometer.

Main technical data: coercive force measuring range from 2,0 to 40 kA/m; full scale deflection error not more than ±4%; time of measuring circle (12±2) s. Testing object requirements: minimal cobalt content 0,15 g; maximal mass 200 g; maximal dimensions 50 × 30 × 20 mm or 35 mm in diameter, height 16 mm.

3. NONDESTRUCTIVE EVALUATION TECHNIQUES BASED ON COERCIVE FORCE MEASUREMENT

3.1. Estimation of technical state of the power plant steam pipelines after long-term operation life.

This chapter is related to the steam pipelines of power plants operated under high pressure (up to 16 MPa) and elevated temperatures (up to 570º C). As a result of long-term operation the initial structural-phase state of materials are transformed. These factors lead to changes in the mechanical characteristics of materials. It is especially important for the areas of pipelines with high level of stress and strain concentration. In this study the regularities of coercive force changes for 12Kh1MF and 15Kh1M1F steels of the steam pipelines bends after long-term operation ($175–280\cdot10^3$h) depending on the phase composition and microdefects are established. The purpose of this investigation is to determine the ultimate values of the coercive force, possible to be applied for prediction of the critical state of steam pipelines.

Materials and methods of investigation. A complex of properties of steam pipelines made of 12Kh1MF and 15Kh1M1F steels was investigated. The steam pipelines were operating at the different Ukrainian thermal power plants (TPP). To determine properties of the metal prior to operation, we studied an element of a pipe of 12Kh1MF steel in the intact state but from the other batch than the operating pipes. Since in the course of startups and shutdowns of power-generating blocks, elements of steam pipelines are operated under the complex action of temperature and force factors (under the combined influence of static and low-cycle loads and variable temperature modes), which noticeably accelerates the degradation of steels, we study the model degradation of 12Kh1MF steam pipeline steel in the as-delivered state in the process of heating up to temperatures of 540, 570, 600, and 630 ^{0}C under the conditions of cyclic loading of specimens of the material at these temperatures. The specimens were subjected to cyclic loading under tensile nominal stresses with different load ratios R = 0.1–0.6 (i.e., different static components) at a frequency of 5 Hz. The ratio $\sigma_m/\sigma^T_{0,2}$ = 0,5…0,8, where $\sigma^T_{0,2}$ is the yield strength of the steel at a chosen temperature, approximately corresponds to the operating conditions of the metal in the maneuvering operating mode of the steam pipeline [15]. The magnetic characteristics of steel subjected to the model degradation were measured after cycling (in the unloaded specimen).

We tested striplike specimens with working part 50×10×3 mm in sizes cut out from various zones of the bends of steam pipelines in the longitudinal direction. The mechanical properties of steels under short-term tension were determined in an UME-10TM tensile-testing machine. Moreover, the specimens were subjected to static stepwise loading in which every subsequent increase in the level of acting nominal stresses σ_{nom} was preceded by the complete unloading of the specimens and coercive force measurements.

The fatigue tests of the metal after in-service degradation in different zones of the bends of steam pipelines were carried out under the conditions of pulsating (R = 0.1) loading cycles with constant values of the range ($\Delta\sigma_{nom}$) at a frequency of 10–12 Hz. The coercive force $\boldsymbol{H_C}$ was measured in the unloaded specimen after a certain number of cycles ΔN. The coercive force $\boldsymbol{H_C}$ was measured by a KRM-Ts device (fig. 1). The device was preliminarily calibrated on calibration blocks (fig. 1).

The changes in the structure and microdamaging were established according to the results of quantitative metallographic analysis of microsections by a NEOPHOT-21 optical microscope and a ZEISS-EVO 40XVP scanning electron microscope. The character and sizes of microdefects were determined also. The mean content of pores is found as the mean area occupied by the pores in the field of view of the microsection. A set of at least three micropores with the distance between the pores equal or close to the size of the micropore is regarded as a chain of pores. The number of pores is evaluated for five fragments of the images of microstructure of steels and their mean content was found.

Results and discussion. The specific features of the degradation processes in the materials of different zones of the bends of tested steam pipelines [16] lead to changes in the coercive force $\boldsymbol{H_{C\,0}}$ measured on specimens prior to mechanical tests. For the stress-free metal, its value increases from 300 to 320 A/m for 12Kh1MF steel and from 270 to 290 A/m for 15Kh1M1F steel in passing from the zone of compression to the zone of tension. In the same range, we recorded the changes in H_C^0 in the templates from the same steam pipelines. In specimens of 12Kh1MF steel in the as-delivered state, H_C^0 = 295 A/m (Table 1 and Fig. 8). After the elastic tensile deformation of the specimens, the coercive force of the metal remains almost constant (Fig. 8) up to the values H_C^T corresponding to the yield strength $\sigma_{0.2}$ of steels in different zones of the bends (Table 1) when the irreversible transformation of the domain structure begins as a result of rotation of the domain boundaries under the conditions of micro- and macroplastic deformations. As the load increases in the region of irreversible plastic strains for $\sigma_{nom} > \sigma_{0,2}$ (Fig. 8), the intense accumulation of defects is accompanied by an abrupt increase in the parameter H_C up to the maximum values H_C^B (depending on the zone of the bends) corresponding to the ultimate strength σ_u of the material of this zone (Fig. 8 and Table 1).

Under static loading, the coercive force increases from the initial value H_C^0 to the critical value H_C^B by about a factor of 1.4 (for 12Kh1MF steel) or by about a factor of 1.7 (for 15Kh1M1F steel) [17, 18]. The accumulation of defects in the zones of the bend of 15Kh1M1F steel under cyclic loading in the elastic region $\Delta\sigma_{nom}$ = 280 MPA < $\sigma_{0,2}$ (Table 1) is observed as a monotonic increase in the coercive force (Fig. 9). For the metal of the neutral and compressed zones of the bend, the increase in the coercive force is insignificant even up to $N \sim 2 \cdot 10^6$ cycles of operation.

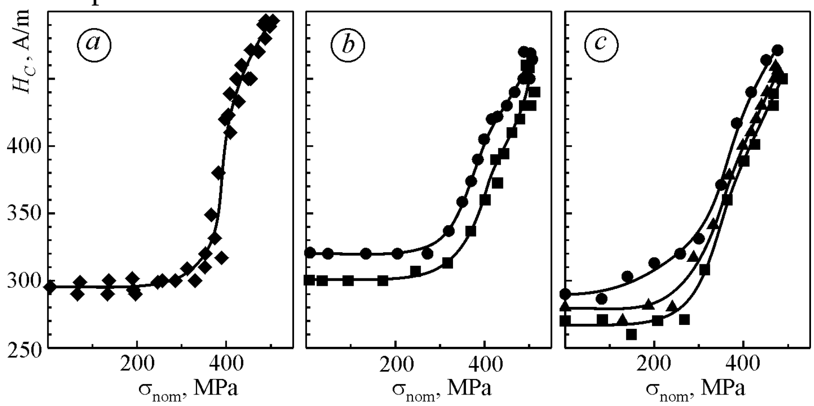

Fig. 8. Behavior of the coercive force under static tension of 12Kh1MF steel in the intact state (a) and in specimens cut out from the bends of steam pipelines after operation: (b) 12Kh1MF steel, (c) 15Kh1M1F steel; (●) stretched zone, (▲) neutral zone, (■) compressed zone.

Table 1. Characteristics of steels

Steel	Zones of the bend	Mechanical					Magnetic		
		$\sigma_{0,2}$	σ_B	δ	ψ	HB	H_C^0	H_C^T	H_C^B
		MPa		%			A/m		
12Kh1MF	Intact state	344	469	19	51	155	295	310	473
	Stretched	280	457	-	70	156	320	322	437
	Neutral	-	-	-	-	163	310	-	-
	Compressed	348	472	-	69	166	300	331	412
12Kh1MF	Stretched	338	470	13	58	146	290	360	470
	Neutral	370	482	12	56	155	280	380	460
	Compressed	405	491	13	58	159	270	390	450

However, in the material of the stretched zone for $N > 2 \cdot 10^5$ cycles, as a result of the intense accumulation of local plastic strains, H_C abruptly increases up to the maximal value, which is close to H_C^B under static loading. In this case, on the surface of the specimen, we observe the formation of a network of fatigue microcracks, which leads to the fracture of the specimen. The procedure of cycling in the region of elastoplastic strains (σ_{nom} = 350 MPa > $\sigma_{0,2}$) under the conditions of low-cycle fatigue intensifies damaging and causes an increase in the coercive force immediately after the first loading cycles. Then the coercive force H_C sharply increases up to the maximum value, which is close to the value H_C^B under static loading for which the specimen fails (Fig. 9). These ultimate values of the coercive force are close for static and cyclic loads and caused by the stress-strain state and the degree of microdamaging of the material. So, the critical state of steam pipelines can be predicted by using these values. It is clear that these values of H_C depend on the structural-phase state of the materials.

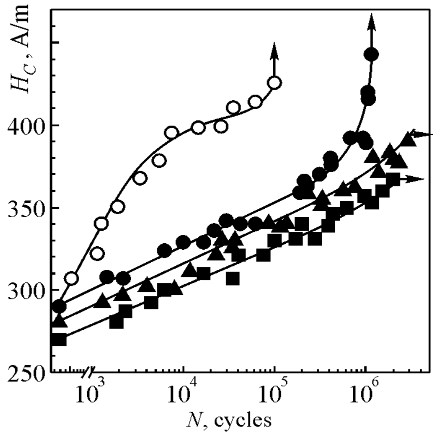

Fig. 9. Behavior of the coercive force under cyclic loading within the stress ranges □σ_{nom} = 280 MPA *(●,▲,■) and 350 MPa (○) for specimens of 15Kh1M1F steel cut out from the bend of a steam pipeline after operation:*
(●,○) stretched zone;
(▲) neutral zone;
(■) compressed zone.

In analyzing the influence of structural factors on the delay of motion of the domain boundaries and retardation of dislocation glide, it was emphasized that this influence is similar for the magnetic and mechanical characteristics of steel, which means that these characteristics are correlated [1]. Thus, in particular, the coercive force $\boldsymbol{H_C}$, as a rule, increases with the yield strength $\sigma_{0,2}$, ultimate strength σ_u , and hardness (HB and HRC) of the material and, hence, as the relative elongation δ and relative narrowing ψ of the material decrease [13, 14, 19–21]. Similar regularities were also established for a heat-resistant steel in the intact state (prior to operation). Thus, after different modes of normalizing of cold-deformed 12Kh1MF steel, its strength ($\sigma_{0,2}$ and σ_u) became 1.5–3 times lower, its plasticity (δ) became 2.5–3.5 times higher, and the coercive force became twice lower [19]. Hence, the heat-treated steels in the intact (as-delivered) state, including the heat-resistant steels of steam pipelines of TPP, are characterized by the presence of correlation relations between their shortterm strength and plasticity characteristics and the coercive force (Fig. 10a): The increase in the latter is caused both by the increase in strength and by the decrease in the plasticity of steel.

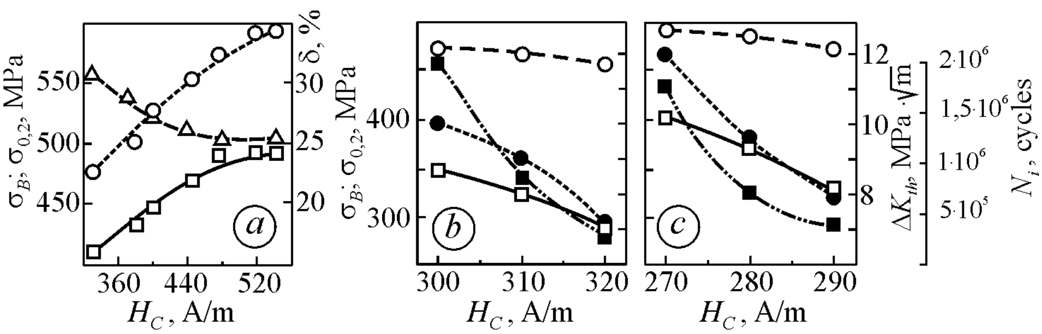

Fig. 10. Relationships of mechanical characteristics versus coercive force for 12Kh1MF steel after different heat treatment regimes (a) and 12Kh1MF (b) and 15Kh1M1F steels (c) after exploitation degradation: ○ *– ultimate strength* σ_B; □ *– yield strength* $\sigma_{0,2}$; △ *– elongation* δ; ● *– fatigue threshold* ΔK_{th}; ■ *– period* N_i *to fatigue macrocrack initiation at* $\Delta\sigma_{nom}$ *= 60…66 MPa [20].*

For 12Kh1MF and 15Kh1M1F steels after long-term operation, absolutely different relationships between the coercive force and the mechanical characteristics were recorded (Figs. 10b, c), as compared with the relationships obtained for steels in the intact state (after heat treatment), when the coercive force decreases as the strength of the steel decreases (Fig.

9a). Obtained results (Table 1 and Figs. 10b, c) indicate that the mechanical characteristics of the steels specified by the current normative document change slightly depending on the degree of degradation, demonstrating some decrease, which is accompanied by an increase in $\boldsymbol{H_C}$. Here, the parameters of fatigue fracture mechanics [20], in particular, cyclic crack resistance characteristics N_i and ΔK_{th} in the stages of initiation and initial growth of a fatigue macrocrack, are more sensitive (Figs. 10b, c). Thus, the large array of literature data on the dependence of the coercive force on the mechanical properties of nondegraded heat-treated steels [1] is unsuitable for the diagnostics of the state of steels of steam pipelines after long-term operation.

The residual service life of bends of steam pipelines is determined by the damage of their metal, and, at present, it is predominantly evaluated from results of metallographic investigations and determination of the degree of damaging. The coercimetric analysis of the bends of pipelines of a number of TPP (indicated above) revealed (Fig. 11) that, for 12Kh1MF and 15Kh1M1F steels, there exist relations between the values of $\boldsymbol{H_C}$ of the metal and the degree of microdamaging, which are bounded by the values of H_C^{base} from below and by H_C^{cr} from above and correspond to the coercive force of the steels in the initial (as-delivered) state and to the averaged values of $\boldsymbol{H_C}$ under conditions of fracture under static and cyclic loading (Figs. 8 and 9). From these relations one can evaluate easily and efficiently the technical state of the metal of bends of steam-pipelines after long-term operation [18].

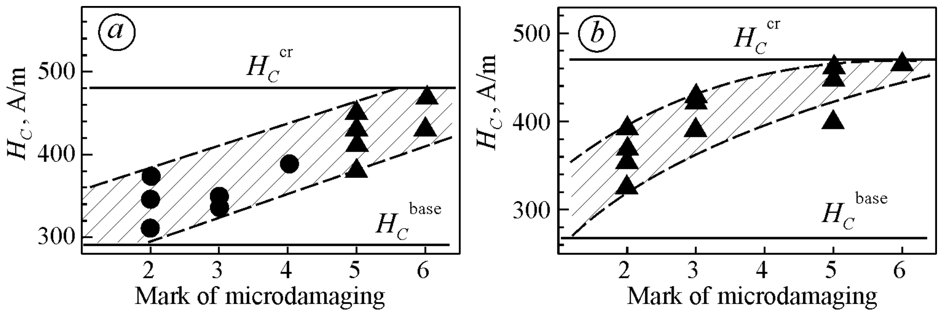

Fig. 11. Dependences of coercive force of degraded 12Kh1MF (a) and 15Kh1M1F (b) steels on the mark of microdamaging: ● – model degradation; ▲ – exploitation degradation in the tensile zone of steam pipeline bends; H_C^{base} – virgin and H_C^{cr} – critical levels of coercive force of steels.

Hence, the possibility of diagnostics of the structural-mechanical state of steels of steam pipelines after long-term operation according to the data of measurements of the coercive force H_C was experimentally justified. We state that it is necessary to form a new database of correlation dependences for the properties of heat-resistant steels degraded in the process of operation on their structural-phase state and the degree of microdamaging because the dependences known for these steels in the intact (as-delivered) state are unsuitable for this kind of diagnostics.

3.2. Estimation of stresses along ship load-bearing elements during operational loading

A large number of ships in service has exhausted its resource or are close to its exhaustion. So, the operational monitoring of the technical condition of the long-used marine shipboard structures can prevent possible accidents. The critical areas of the ship structure are considered 1) the middle part of the vessel; 2) areas located in a quarter of the ship length from the rostrum and stern perpendiculars and 3) the area of the transition of the deck into the desk superstructure [21]. According to the circular of the International Maritime Organization, all vessels with a carrying capacity more than 20000 tons are recommended to be equipped with strain gauge monitoring systems for monitoring of the ship technical condition [22].

Tensometric sensors are recommended to be installed stationary in the middle part of the ship's hull (the area of the midship-clams) and in places located at a distance of 0,25 (where - length of the ship) from the rostrum and stern perpendiculars.

An indirect method for determining the level of mechanical stress, constructed on measuring the coercive force of the material of the surveyed structure, can be effective for diagnosing the technical condition of the vessel [8, 10, 11, 14, 17, 23, 24]. This was confirmed experimentally during ship repairs [23]. At the same time, the mobility of the method based on the coercive force measurements makes it possible to carry out an individual analysis of the mechanical stress distribution in the elements of the design of a particular vessel, which makes it possible to increase the reliability of the monitoring [23, 24].

In this study the new concept of monitoring the technical condition of ships based on the coercive force measurements is proposed.

To determine the distribution of coercive force along the ship structure elements the upper horizontal surfaces of coamings located on both sides of the vessel are selected. Such choice is founded due to the fact that the coamings of cargo type ship applied for river-sea navigation are accessible for instrument control in contrast to other longitudinal beams of this type ships. Coaming are important bearing elements of the ship that ensure its longitudinal strength, and holds can be considered as structural stress concentrators (Fig. 12) [24].

Measurement of the coercive force H_c was carried out by a KRM-Ts type device (fig. 1) [13]. Measurement was carried out on a “river-sea" type cargo ship, which has been in operation since 1980. The planned lifetime of the court is 25 years. The material of the coamings of the investigated ship is 09G2S steel. The longitudinal coordinate of the points of measurement of the coercive force H_c was determined by the number. Measurements were made at points on the horizontal desks of the coamings (fig. 12), which correspond to each 5th bulkhead. For the studied vessel, the distance between each fifth bulkhead was equal to 2.5 m. The points of the value of the coercive force along the longitudinal comings can be precisely determined and transferred to the general plan of the inspected ship. In this case, the longitudinal and transverse components of the coercive force, which corresponded to the longitudinal along the X axis and transverse along the Y axis, were directed to the directions of the magnetic field of magnetization (fig. 2).

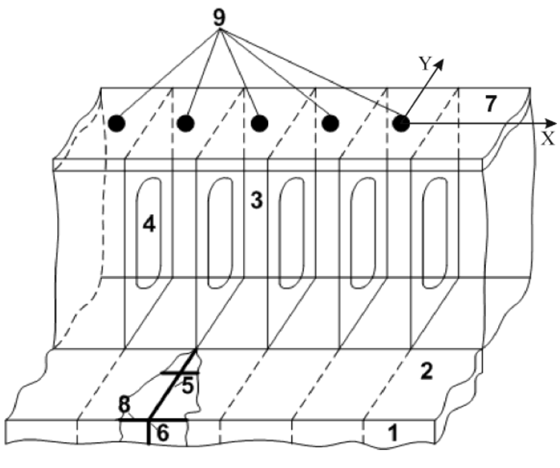

Fig. 12. Location of the points of the coercive force measurements along the ship coaming: 1 - board of the ship; 2 - deck; 3 - coaming; 4 - stands of the coaming; 5 - deck beam; 6 - bulkhead; 7 - horizontal desk of the coaming; 8 – sub-stringer; 9 - measuring points.

Results and discussion. Measurements of the distribution of coercive forces H_c along the load-carrying element on the "river-sea" type ship were conducted in different conditions of their operation and with different loading modes. After processing the results of measurements on one of the vessels surveyed, charts of the change in the coercive force were obtained according to the measurement point numbers No in ballast (fig. 13a) and in the loaded state (fig. 13b).

The analysis of the distribution of the value of the coercive force showed (fig. 13) that the highest values are observed in the zone of a bulkheads by numbers 50 (point 4), 57 (point 5), 85 (point 6), 135 (point 7) and 190 (point 8). These zones can be recognized as individual critical ones for inspected ship and can be used for further monitoring. The analysis revealed that the identified critical zones coincide for the ballast mode (fig. 13a) and for the ship under full load (fig. 13b). Consequently, the identified critical zones are available under different loading conditions of the ship and are individual for each ship.

Note that boat loading may lead to a redistribution of initial stresses. This can lead to the fact that at certain points (4 and 5 on fig. 13) the tension during boat loading decreases.

It should be noted that the critical areas of maximum mechanical stresses established for the investigated ship differ significantly from the recommendations of the International Maritime Organization [22]. This made it possible to propose a basic concept for monitoring ship structures under operating conditions, which (unlike traditional approaches) takes into account the specific features of a particular ship [23, 24]. Due this concept further monitoring is carried out by placing the coercive force sensors in the defined critical zones and measuring the changes of the coercive force in the process of further exploitation (fig. 14).

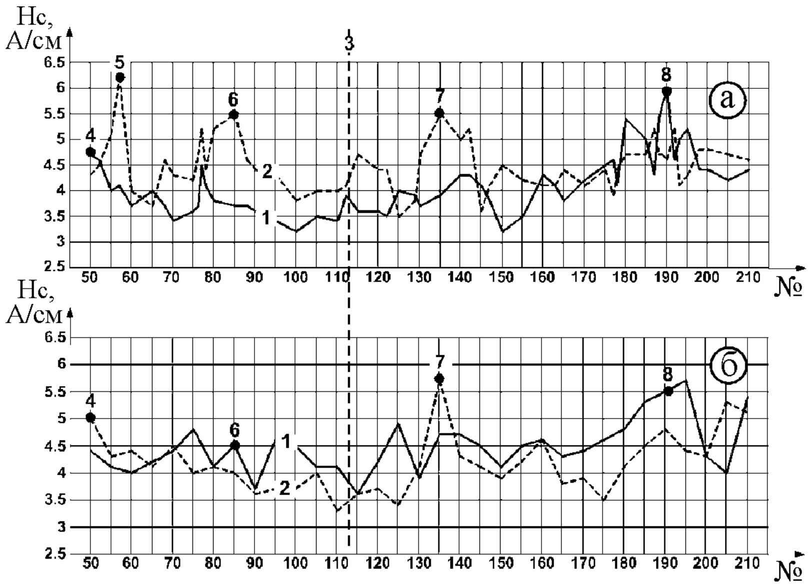

Fig. 13. Distribution of the coercive force along the coamings according to the bulkhead numbers in ballast (a) and in loaded conditions (b): 1 - longitudinal H_c component; 2 - transverse H_c component; 3 - midship section; 4-8 – revealed critical zones.

Fig. 14. The process of coercive force measurements along the "river-sea" type ship coaming.

To determine the mechanical stresses of ship structures in critical areas, an appropriate correlation between the stress state and the material coercive force is used. To estimate the critical state of the ship's structural elements, the values of coercive force predetermined for the material can be used and correspond to the yield strength and strength respectively. For the investigated steel of type 09G2C, the corresponding values of the coercive force are = 7.5 A/cm and = 9.5 A/cm respectively [24].

So, the proposed concept is based on preliminary determination of critical zones of bearing elements of ship structures, which allows to take into account the individual features of the inspected ship and to increase the monitoring reliability [23, 24].

3.3. Hard alloys products evaluation by coercive force measurement in open magnetic circuit

Physical-mechanics characteristics of products from sintering hard alloys strongly depend on sintering mode parameters. The functional relations between this characteristics and coercive force are usually used for nondestructive testing.

The coercive force of hard alloys is determined by state of ferromagnetic constituent – cobalt phase. This phase is a solid solution of tungsten and carbon in cobalt. Depending on content of carbon in a hard alloy amount of dissolved in cobalt tungsten, will be greater (at the lack of carbon) or less (at the surplus of carbon). That’s why the magnetization of cobalt phase will be different. As a result, depending on chemical composition of mixture, procedures of its production and sintering conditions, for different lots of products manufactured from the same hard alloy grade coercive force value will be different within wide range. So, the coercive force can be used as the quality indicator for hard alloys products. For this purpose the VKS-968 type coercimeter (fig. 6) can be applied. The hard alloys products possible to be evaluated in open magnetic circuit by VKS-968 type coercimeter are presented on fig. 15.

Fig. 15. Hard alloys products evaluated by coercive force measurements in open magnetic circuit.

Magnetic features of hard alloys also depend on the modes of heat treatment applied for the improvement of mechanical properties, in particular for their strengthening by a tempering. For alloys, tempered with high-speed cooling, the substantial increase of coercive force is observed. The maximal increase of coercive force after a tempering reaches up to 14% from the level in initial state [25]. Dependences of coercive force on the tempering temperature for tungsten-cobalt hard alloys VK6 (WC – 94%, Co – 6%, $\sigma_{bend} \geq 150$ kg/mm^2, *HRA* ≥ 88,5), VK15 (WC – 85%, Co – 15%, $\sigma_{bend} \geq 180$ kg/mm^2, *HRA* ≥ 86,1) and VK25 (WC – 75%, Co – 25%, $\sigma_{bend} \geq 200$ kg/mm^2, *HRA* ≥ 82,0) are presented on fig. 16 (σ_{bend} – bending strength).

The coercive force $\boldsymbol{H_C}$ for some hard alloys grades before and after tempering are presented on the Tabl. 2 [26].

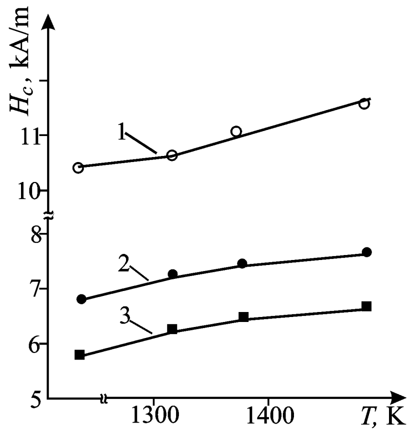

Fig. 16. The dependence of coercive force $\boldsymbol{H_C}$ on the tempering temperature for tungsten-cobalt hard alloys: 1 – VK6, 2 – VK15, 3 – VK25.

Table 2. Tungsten-cobalt hard alloys coercive force dependence on the tempering modes.

Hard alloy grade	Coercive force value, kA/m						
	In initial state	Tempering temperature 1200°C			Tempering temperature 1000°C		
		Air quenching	Water quenching	Oil quenching, 40°C	Air quenching	Water quenching	Water quenching
BK6	10,74	10,98	11,30	11,70	–	–	–
BK8	9,39	9,55	10,19	19,11	–	9,63	9,79
BK8B	7,80	–	–	–	7,96	8,36	8,44
BK15	4,77	–	–	–	–	–	5,73
BK25	5,41	5,57	5,73	6,21	–	5,89	5,81

Tempering was carrying out by quenching in various mediums. This table data show that coercive force $\boldsymbol{H_C}$ of hard alloy samples quenching with high-rate is increase. Coercive force of samples cooled in air increasing insignificantly compared to its value in the initial state. The maximal coercive force increase (about 14%) after tempering takes place after cooling in oil.

For all inspected tungsten-cobalt hard alloys products the ultimate (critical) value of coercive force were preliminary defined which to guarantee the quality demands [25].

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