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EVALUATION OF THE STRUCTURES METAL DAMAGE UNDER THE STATIC AND CYCLIC LOADINGS ACCORDING TO THE COERSIVE FORCE VALUE

Oleksii Gopkalo[1]; Gennadii Bezlyudko[2]; Volodymyr Nekhotiashchiy[3]

[1]Institute for Problems of Strength named after G.S. Pisarenko, National Academy of Sciences of Ukraine, Kyiv
[2]LLC "Special Scientific Developments", Kharkiv, Ukraine
[3]Institute of Electric Welding named after E.O. Paton, National Academy of Sciences of Ukraine, Kyiv

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Summary. *The results of experimental investigations of the damage degree of the ferromagnetic steel 05kp and austenitic (paramagnetic in the initial state) steel AISI 304 under the static and cyclic loading according to the coercive force (Hc) value are presented. The stages of the processes of the damage accumulation are determined: the growth of the coercive force values corresponds to the elastic-plastic strain (crack initiation stage), and the decrease of their values is caused by the failure of the metal solidity caused by the formation of pores and cracks (crack development stage). Identification of the damage accumulation stages by changing the direction of the coercive force kinetics after a certain number of run cycles allows us to construct a curve of irreversible damage (the French line type) and to evaluate the cyclic durability not according to the fatigue curve (destruction) of the metal, as it is considered in engineering, but at the stage of the crack initiation, which significantly reduces the risk of destruction. The obtained results can be the basis for the development of new approaches to the rapid assessment of the residual life of the structures metal by a simple non-destructive method.*
Key words*: structurescope, specimen working part, coercive force, strain, fatigue cracks, damage.*

Statement of the problem. The latest papers in the field of the magnet structurescopy made possible to find the similarity of magnetic and mechanical properties of some ferromagnetic structural steels [1, 2]. The coercive force was chosen to be the main magnetic parameter (*Hc, A/cm*) as the most sensitive as to the steel structure dislocation density [3] and is of the linear dependence on the mechanical properties. As the result it could be possible to model the tension diagram according to the coercive force changes data.

Beside the investigations of the magnetic properties of the ferromagnetic steels, the possibility to use and change these properties in the austenitic (paramagnetic in the initial state) steels under static or cyclic deformation for the evaluation of their strength and damage according to the coercive force can be of the scientific and practical interest. Because of the found sufficient differences of the ferromagnetic and paramagnetic steels coercive force respond to the mechanical loading, the main attention in this paper is paid to the investigation of the austenitic steel, which being loaded, demonstrates much higher values of the coercive force, than those for the ferromagnetic steel, the effect of unloading on the value *Hc* being not available. In the paper in question the ability of the austenite $\gamma \rightarrow \alpha$ to be structurally transformed into the austenitic steels and the appearance of the ferromagnetic phase (α-Fe), which cause the change of the metal magnetic properties from the paramagnetic state to the ferromagnetic one, has been used under the external deformation effects. Under the cyclic loading beside these transformations the initiation and accumulation of the micro-damages in the metal take place, which result in the magnetic hysteresis loop sizes, the coercive force values

Corresponding author: Oleksii Gopkalo; e-mail: apg@ipp.kiev.ua

in particular. The application of the coercive control under the fatigue loading will make possible to carry out effective diagnosis of the current state of the structural elements beside the other available methods of the non-destructive control [4].

Analysis of the available results of investigations. Among the other non-destructive methods of control the coercive-metric evaluation of the metal damage of the structures made of austenitic stainless steels (non-magnetic foremost) is rather promising. According to the obtained data in the paper [5] the plastic deformation of the austenitic steel increased the value of the coercive force in 10 – 30 times and the volume of the ferromagnetic phase (α-Fe) in 15 – 150 times relatively the initial state. It results in the fact, that the level of hazard of the permissible metal deformation in the conventional structures can be evaluated according to the boundary values of the metal magnetic properties. The other methods of the non-destructive control have not revealed up till now the information sensitivity to the processes of the metal deformation.

Now under the static and cyclic loadings the whole process of the damages accumulation is divided into two main stages: crack initiation stage and crack propagation stage, as the regularities of the processes of plastic deformation and fracture under different types of loading possess many similarities [6, 7, 8]. In its turn the crack initiation stage includes the stages of static and cyclic micro-creep, the stages of static and cyclic creep (the defects of the atom sizes and initiation submicrocracks of the thousands of angstrom sizes being initiated), and the stage of the deformation hardening, when the submicrocracks of about 1 – 2 mkm size are being initiated. Under tension the crack initiation stage is completed, when maximum loading is obtained and the neck forming is started. Under the cyclic loading the stage of the cyclic hardening (softening) is completed, when the irreversible damage line (the French line) is approached. Similarly to the static deformation the development of damages as the submicrocracks initiation [9] is noticed at this stage together with the processes of the deformation hardening. The stage of the fatigue cracks development is usually described by the kinetic diagrams of the fatigue fracture (the dependence between the fatigue crack growth rate and the *SIF* range).

Under tension and cyclic deformation the stress distribution along the products cross-section are non-uniform enough not only because of the available roughness and the stress concentration, but because of the plastic deformation of the part surface, which is very non-uniform, both on the surface and in the depth, and under the conditions of the uniform stress state it is initiated earlier, than that in its centre [10]. The carried out experimental investigations showed, for example [11], that under the uniform stress state the surface layer in the low carbon steel has the creep boundary by 25% lower, than that of the main metal, and according to some other data [12] the conventional creep boundary of the most thin specimens is of the 20% of the thick specimens value, the plastic flow being on the surface at the time, when the centre is in the elastic state. Caused by it, the fracture under the cyclic deformation, as a rule, is initiated from the surface in the local areas.

Because of that under static and cyclic loadings the surface layers of the material are deformed and accumulate damages earlier, than the main metal, which results in the non-uniformity of the magnetic properties distribution along the products cross-section. Thus, the accuracy of the magnetic forces measurement (coercive force) in the local surface areas will depend on the sensor size and the depth of the metal magnetization. That is why, while investigating the mechanical properties of metals according to the change of values of the coercive force in the most damaged local areas of the surface layers, it is necessary to use the coercive meters with the small-size sensors of not deep magnetization.

Statement of the task. The experimental investigations on the effect of the static or cyclic loadings of different in the magnetic properties (ferromagnetic and paramagnetic) steels on the kinetics of the coercive force *Hc* for finding the accumulation processes of the corresponding damages have been performed. The work was carried out in the laboratories of the Institute for Problems of Strength named after G.S. Pisarenko of the National Academy of Science of Ukraine and the Institute of Electric Welding named after E.O. Paton of the National Academy of Science of Ukraine.

Method and the results of experimental investigations. The object of investigation was the metal of the roll sheet steel 05kp of the 3mm thickness and metal from the pipes ∅76x3 and ∅159x4 with the longitudinal weld seam from the austenitic steel AISI 304 (08H18N9) produced in Italy in accordance with the European standard EN10217-7.

The blanks for the laboratory specimens from the austenitic steel were cut in the longitudinal direction of the pipe and were under thermal treatment according to the regime: heating till 800^0C with the heating rate (4-5) ^{0}C/min, soaking – 2 hours, cooling together with the furnace.

Long and short laboratory specimens of 150x14x3 mm and 28x14x3,6 mm working area correspondingly were used for the static and cyclic loading tests. The tensile and small-cycle sign-variable (small-cycle fatigue) tests of the short specimens were carried out on the upgraded electro-hydraulic testing machine UE-20 (SKBIM, Russia) according to the GOST 1497-84, 25.502-79 and GOST 25.505-85. Small-cycle fatigue tests of the symmetric cycle of the axis tension-stress controlling the strain amplitude (rigid loading regime) were carried out with the constant deformation rate *6%/min* (Fig. 1). The cyclic вітнулевий zero-strain tension tests of the 2 cycle/min frequency of the long specimens were carried out on the testing machine IP-4M (TsNIITMASH, Russia), provided by the drive of the cyclic load lift on the lever. All mentioned tests were carried out at the room temperature.

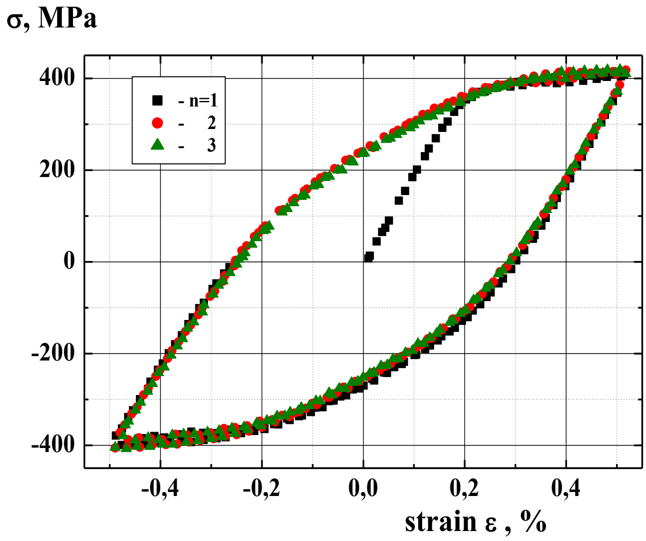


Figure 1. Diagram of cyclic deformation of a short specimen with the strain amplitude $\varepsilon_a = \pm 0{,}5\%$

The measurements of the coercive force *Hc* in the specimen were performed by the structurescope KRM-C-K2M (LLC “Special Scientific Developments”, Kharkiv) according to the standards ICO4301, GOST 30415-96 and methodic recommendations RD ISC “Kran” 07/97/02 (Russia), MV 0.00-7.01-05 (Ukraine). To measure the coercive force value the structure scopes with the variety of sensors different in the measurement base and sizes were used: standard sensor D65 (base – 65mm), small-base sensor D27 (base –27mm) and the sensor with the shortened base D12 (base – 12mm), the measurement base being the distance between the external shoes of the magnet pole. Depending on the material and the sensor base the magnetization depth can be: for the sensor D63 – up to 30mm, D27 – up to 4mm, and D12 – to 1mm.

The measurement of the ferromagnetic phase (α-Fe) volume in the austenitic steel was carried out taking advantage of the ferritometer “Ferritghaltmesser 1.053 Forster”.

Because of the non-uniformity of the mechanical properties distribution along the thickness and the material surface, as well as because of the variety of concentrators and other reasons, the change of structure is the most effective under the cyclic loading in the surface layers of the metal, which demonstrate the damages accumulation and contribute to the coercive force *Hc* value. As the laboratory specimens were produced from the pipe metal with the longitudinal weld seam made of the sheet steel and are of different degrees of the accumulated technological damages on the external and internal surfaces, being under the tensile and cyclic strain testing, the measurement of the coercive force was performed by the smaller base sensor *Д4* on the both surfaces and the sensor magnets pole shoes were located in the longitudinal and transversal directions of the specimen.

Results of the experimental investigation of the steel 05kp under static and cyclic tension. In Fig.2 the diagram of the long specimens tension is presented as well as the dependence of the coercive force *Hc* measured by the sensor D65 on the strain (ε) under gradual short-term step-by-step of the 5% strain step loading (*P*) and unloading to the value *P=0*. In Fig.3 the strain kinetics and the coercive force *Hc* values according to the number of the applied force cycles and unloading under the cyclic tension of the 2 cycles/min frequency, are presented.

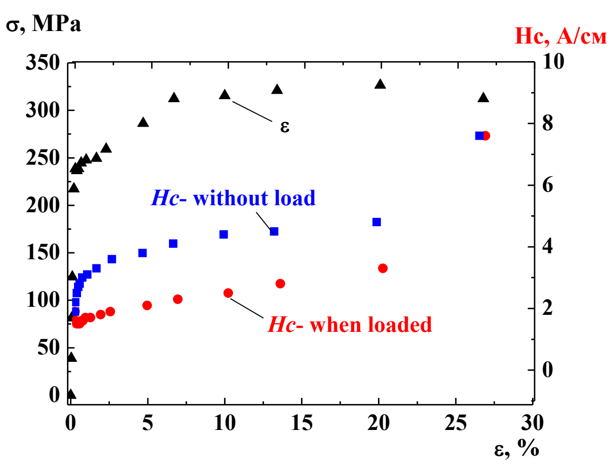


Figure 2. Diagram of long samples tension and dependence of the coercitive force Hs on strain (ε) under short-term gradual step-by-step loading with unloading

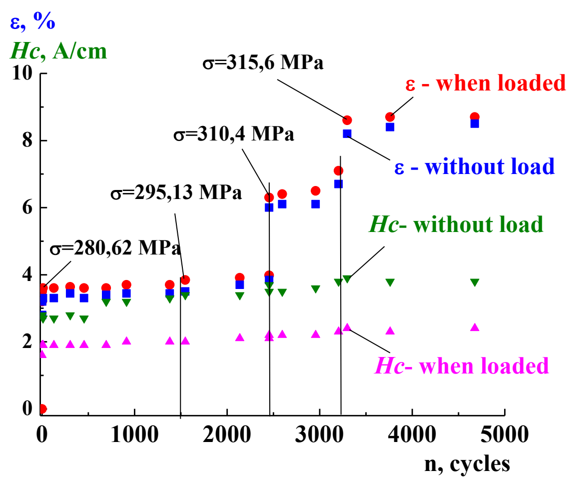


Figure 3. Strain kinetics and the coercive force Hc values according to the number of cycles of applied force with unloading under cyclic tension of 2 cycles / min frequency

The data obtained testify, that under the static tension with the gradual step-by-step increase of loading with unloading at every step and under the cyclic tension in the unloaded state, the coercive force values are about by 50% greater than those of the loaded state at the same step of loading. It should be noted, that the critical values *Hc* before fracture in the loaded and unloaded states coincide and equal 7,8 A/cm. The values of the coercive force before fracture are about in 4 times higher, than those similar values at the initial state of the metal.

Results of experimental investigation of the steel AISI 304 under tension. The tension diagram, dependence of the coercive force *Hc* measured by the D27 sensor and the ferromagnetic phase (α-Fe) volume on the strain (ε) under the static tension of the short specimens, are presented in Fig. 4. It should be noted, that at the step-by-step increase of tension strain by 5% the increase of the coercive force values is noticed only, when the strain equals ~ 25% (at the tension, which is lower than that of the metal ultimate strength, the drastic decrease of the *Hc* values being under the further strain. At the step-by-step loading with unloading the values of the coercive force in the loaded and unloaded states coincide. At the initial loading stages the changes of the coercive force *Hc* are more affected by the strain change, than those affected by the ferromagnetic phase (α-Fe) being formed in the austenitic steel (γ -Fe), and consists of the martensite – and ferrite – strains, which, being of the ultimate strain values (ε ≥ 40%), becomes of the avalanche-type nature. One of the reasons of such behavior of the coercive force can be the decrease of the residual compressing stresses, caused by the decrease of the metal density, resulted from the crystals damage accumulation pores and cavities appearance under the elastic tensile strain [13].

Application of the decreased base structurescope D12 made possible to investigate the coercive force values distribution along the length of the specimen working area under tension and sign-variable strain and to build the *Hc* kinetics in the local surface zone of the specimen. In Fig. 5 the distribution of the accumulated strains and the coercive force *Hc* along the working length of the external surface of the specimen from the pipe under the step-by-step increase of the tensile strain by 5% is presented. Under the tension up to the ~ 25% strain the increase of the coercive force to 67,0 A/cm in the most deformed area of the specimen and further tension take place, the decrease of the *Hc* values to 15,3 A/cm occurs under fracture.

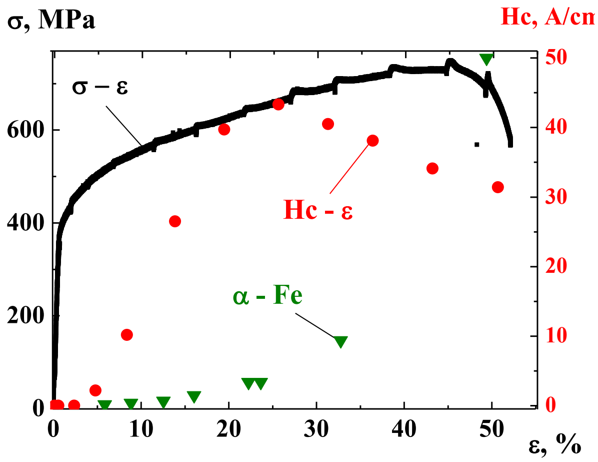


Figure 4. Strain values kinetics under static tension of short specimens and coercive force Hc measured by a low-frequency D27 sensor

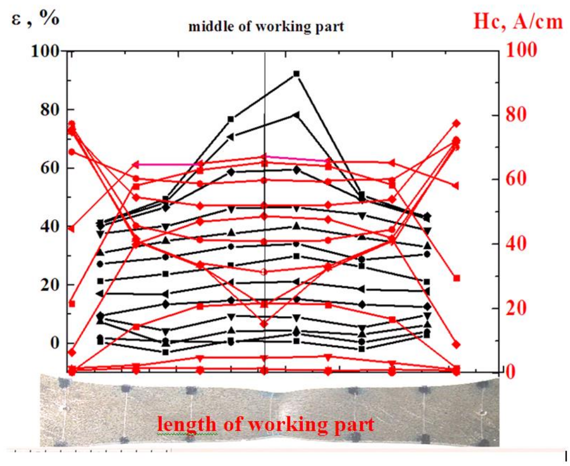


Figure 5. Distribution of strains (black lines) and the coercive force *Hc* (red lines) measured by the sensor D12 along the working length of the external surface of the working part of the short specimen under tension

In Fig. 6 the dependence of the coercive force values measured by the sensor D12 on the accumulated strains in the most deformed local area (fracture) of the specimen under tension, when the sensor magnets shoe poles are located along and across the external surface of the working area of the specimen from pipe is presented. When the magnets shoe poles are located in the longitudinal direction of the specimen working area, the maximum values of the coercive force are by 13% higher, than similar ones, the magnets shoe poles being located in the transversal direction. The raising and dropping areas on the graphs testify the step-by-step mechanism and the change of the prevailing mechanisms of the damages accumulation in the metal under tension. The elasto-plastic strain corresponds to the raising area, the pores and cracks initiation and development to the dropping area.

In the paper [14, 15, 16] it was stated, that under static strain the plastic deformation and damages accumulated before the neck formation are classified as the period of the crack initiation, and the neck-forming and further fracture as the period of the crack development.

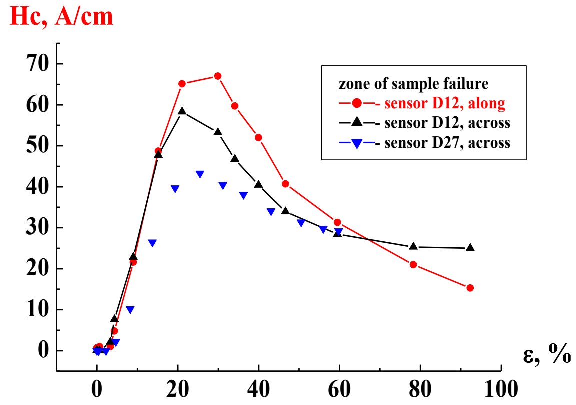


Figure 6. Dependence of the coercive force values measured by the sensor D12 and D27 caused by the accumulated strain (ε) in the most deformed local zone (fracture) of the specimen under tension, when the poles of the sensor magnets are positioned along and across the outer surface of the working part of the specimen from the pipe

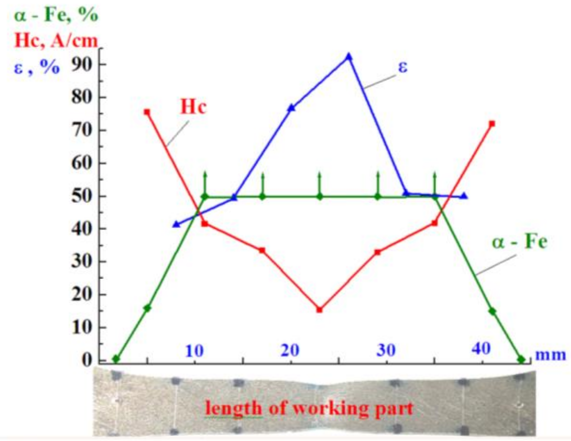


Figure 7. Distribution of the ferromagnetic phase (α-Fe) volume, the coercive force *Nc*, and the accumulated strains ε along the working length of the specimen after tensile fracture

The obtained results testify, that under tension to the accumulated strain values – 25% and stresses being below the ultimate strength, the coercive force increase is caused by the elasto-plastic strain of the steel, which increases the magnetization of metal (coercive force), and the decrease of the *Hc* values at the further strain till the ultimate strength – the pores and cracks initiation (the metal rigidity failure resulting in the decrease of the magnetic properties). Thus, according to the mentioned above classification under the tension causing the neck-forming (metal ultimate strength), the crack initiation stage consists of two stages: the stage of plastic strain resulting in the increase of the coercive force and the stage of the pores formation, when the decrease of the *Hc* values occurs. Under further tension from the ultimate strength till the fracture the increase of the pores and cracks number and sizes occurs. These assumptions are based on the results of the small-cyclic settings of similar specimens (data are presented below), where the change of the kinetics direction and the decrease of the coercive force values are caused by the intensive fatigue cracks initiation and development in comparison with the less intensive elasto-plastic strain.

Thus, according to the coercive force *Hc* value on the raising or dropping areas of the curve, the residual metal strength under tension can be evaluated. In the conventional structures the most deformed areas and the direction of the main stresses can be found according to the position of the sensor magnets shoe poles relatively the investigated surface.

In Fig. 8 the data on the ferromagnetic phase (α-Fe) volume distribution, coercive force *Hc* and the accumulated strains ε along the working length of the specimen under tension after the fracture, are presented. The presented data testify, that the strain accumulation being above 25% (in the case in question after the fracture the accumulated strain in all investigated zones of the working area of the specimen exceeded 40%), the decrease of the coercive force values occurs, which is caused by the metal rigidity failure, and does not result in the increase of the ferromagnetic phase (α-Fe) volume. Unfortunately, we failed to measure the values of the ferromagnetic phase (α-Fe) volume in the centre part of the specimen, because of the limitation

(50%) of the measurement range of the applied in this work ferritometer (exceeding of the (α-Fe) values by more than 50% is marked in the figure by the arrows). The strain increase (plastic at first, and then that resulted from the increase of the pores and cracks number and sizes) in the investigated zones of the working area of the specimen causes the increase of the ferromagnetic phase (α-Fe) volume.

The obtained data demonstrate the complex deformation processes and the pore-crack initiation, which affect the metal magnetic properties and need further physical investigations.

Results of the experimental investigations of the steel AISI 304 under cyclic loading. Because of non-uniformity of the mechanical properties and stresses distribution along the products cross-section, which causes non-uniformity of the magnetic properties distribution, the experimental investigations dependence of the structurescope sensor base determining the square and the depth of the metal magnetization on the coercive force value, were carried out in this paper for the conditions of the cyclic loading.

In Fig. 8 the kinetics of the coercive force values according to the loading cycles with the sign-variable strain amplitude $\varepsilon_a = \pm 0{,}4\%$ depending on the sensors measurement base is shown. Due to the obtained data it follows, that when the measurement base decreases (measurement location increase), the coercive force *Hc* value increases too. Thus, application of the structurescope of not deep magnetization with the decreased sensor base D12 makes possible to obtain greater values of the coercive force and to investigate its kinetics more precisely in the surface local zones of the metal under tension and cyclic loading.

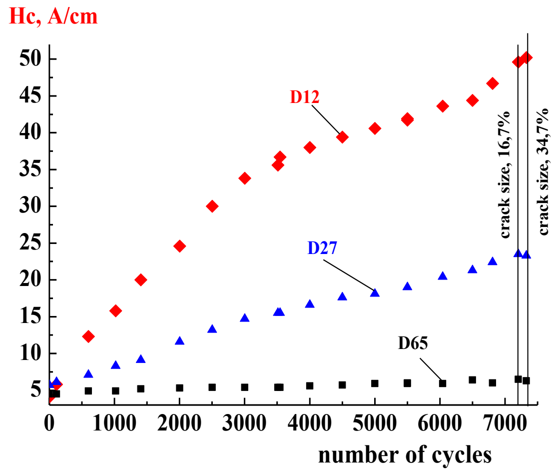


Figure 8. Kinetics of the coercive force values in terms of the number of working cycles with the amplitude $\varepsilon_a = \pm 0{,}4\%$ of the sign-variable strain depending on the sensor measurement base

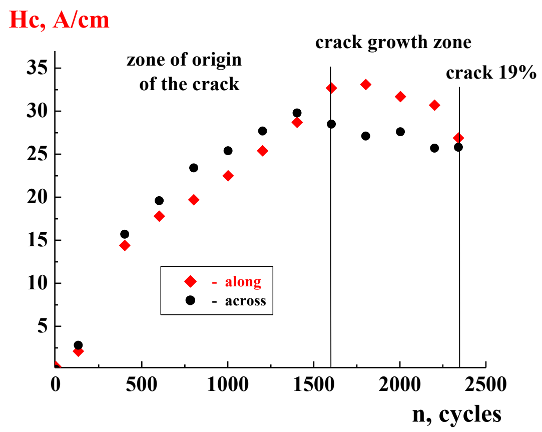


Figure 9. Kinetics of the coercive force Hc measured by the D12 sensor in the fracture zone in terms of the number of load cycles with the amplitude $\varepsilon_a = \pm 0{,}4\%$ of the sign-variable strain depending on the location of the poles of the sensor magnets along or across the external surface of the specimen from the pipe

In Fig. 9 the coercive force kinetics measured by the sensor D12 in the fracture zone according to the loading cycles with the sign-variable strain $\varepsilon_a = \pm 0{,}5\%$ amplitude depending on the location of the sensor magnets shoe poles along or across the external surface of the specimen from the pipe, is presented.

The fatigue crack initiation (metal rigidity failure) in the fracture zone after 1600 cycles of the cyclic sign-variable strain caused the break and change of the coercive force kinetics direction according to the loading cycles. It should be noted, that in the fracture zone under cyclic strain, when the sensor magnets shoe poles are located along the external surface of the specimen from the pipe, the maximum values of the coercive force similar to those under tension, exceed similar values by 13%, when the sensor magnets shoe poles are located across the working area of the specimen.

Under the cyclic sign-variable strain being in operation during 1600 loading cycles, the main fatigue crack has been initiated on the external surface in the upper middle working area of the specimen from the pipe. In Fig. 10 the photo of the cracked specimen on the external surface of the specimen after the cyclic run before the main crack initiation (in the upper middle area of the specimen) of the 19% square of the nominal cross-section, is presented. Beside the main crack the initiation of some smaller cracks (~ 1 mm) in the lower area of the specimen occurred. It should be noted, that the through fatigue cracks were initiated and developed only on the external surface of the specimen, in its internal surface they were not available.

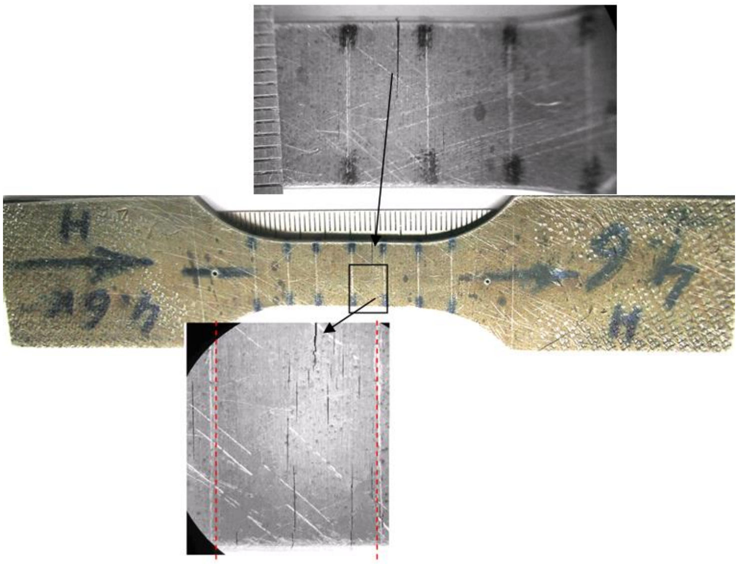


Figure 10. Photo of the cracked specimen on its external working part from the pipe after cyclic run before the main crack initiation of the 19% size of the nominal cross-section

In Fig. 11 the coercive force *Hc* kinetics is presented according to the loading cycles number on the external and internal surfaces of the specimen in the fracture zone, when the sensor magnets shoe poles are located along the working length of the specimen. The crack initiation on the external surface of the specimen causes the decrease of the coercive force values as the result of the magnetic properties decrease. At the same time on the internal surface, where the elasto-plastic strain occurs and the fatigue crack are not available, the growth of *Hc* takes place and its kinetics direction change is seen. It testifies the fact, that under the cyclic loading the decrease of the coercive force values on the external surface of the specimen from the pipe is the result of the material rigidity failure (initiation and effective development of the fatigue crack) along with the sufficiently less elasto-plastic strain. Here, the further growth of *Hc* occurs being caused by the plastic strain on the internal surface of the specimen from the pipe, where the cracks are not available (the material rigidity failure does not occur), and the change of its kinetics direction is the result of the sensor sensitivity to the available under-surface cracks. Such condition testifies the fact of possibility to reveal the under-surface cracks by the structurescope with the small-size sensor of not deep magnetization.

The rupture on the coercive force kinetics curve according to the number of the loading cycles under the cyclic sign-variable strain (see Fig. 9) testifies the step-by-step nature of the metal fracture processes: the growth of the coercive force values corresponds to the elasto-plastic strain (crack initiation stage), and the decrease of the *Hc* values – to the crack development stage caused by the decrease of the metal magnetic properties at its rigidity failure. Thus, under the cyclic loading the application of the structurescopy makes possible to reveal the moment of the metal rigidity failure according to the change of the coercive force kinetics direction after some period of the operation life and to build the curve of the irreversible damage (the French line type) and to estimate the cyclic durability not according to the metal fatigue (fracture) curve as it is considered to be in engineering, but at the stage of the crack initiation stage, which sufficiently contributes to the decrease of the fracture risks.

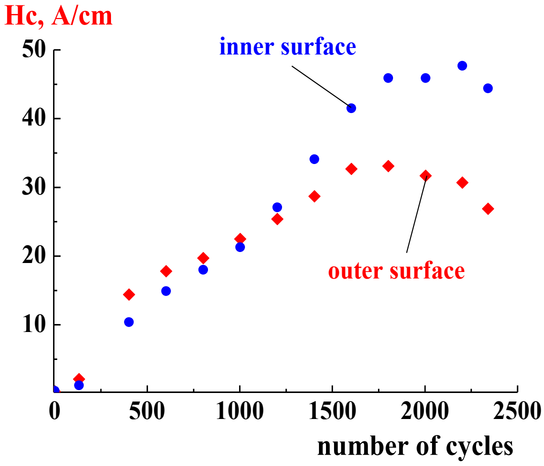


Figure 11. Kinetics of the coercive force on the external and internal surfaces of the specimen from the pipe in the zone of destruction at the position of the sensor magnets shoe poles along the working length of the specimen under cyclic strain with the amplitude $\varepsilon_a = \pm 0{,}5\%$

In Fig. 12 a, b the distribution of the coercive force *Hc* values on the external surface of the working length of the specimen under the cyclic sign-variable strain with the amplitude $\varepsilon_a = \pm 0{,}5\%$, when the sensor magnets shoe poles are located along (a) and across (b) the specimen from pipe is presented. The difference of the coercive force fields distribution, when the magnets shoe poles are located along and across the external working surface of the specimen, is that of the insufficient (~ 13%) differences in the *Hc* values.

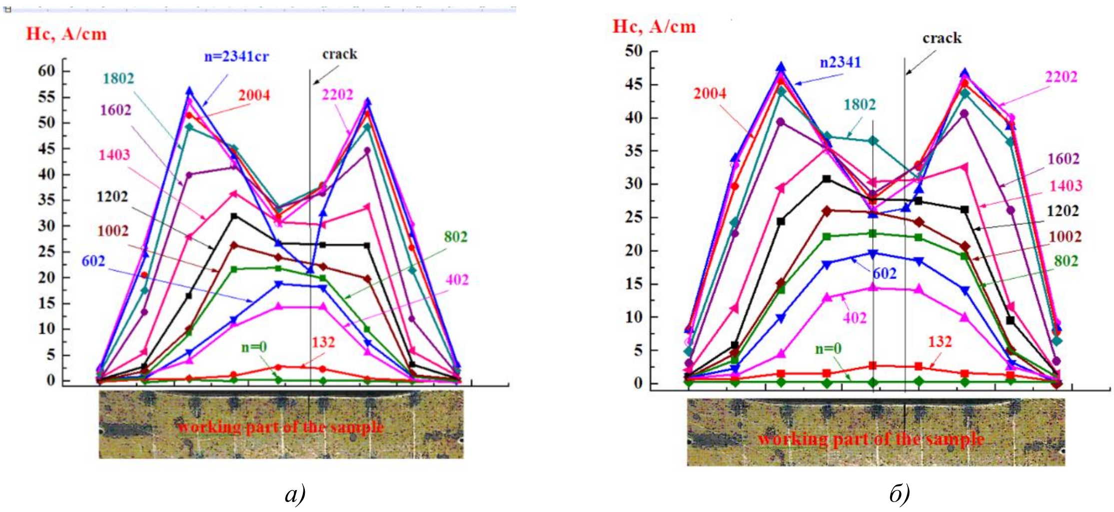


Figure 12. Distribution of the coercive force Hc values on the external surface of the working length of the specimen under cyclic strain with the amplitude of the elastic-plastic strain $\varepsilon_a = \pm 0{,}5\%$ at the position of the sensor magnets shoe poles along (a) and across (b) the specimen from the pipe

In Fig. 13 the data on the ferromagnetic phase (α-Fe) volume and the coercive force *Hc* distribution along the working length of the specimen after the sign-variable cyclic strain before the fracture with the elasto-plastic strain amplitude $\varepsilon_a = \pm 0{,}5\%$ are presented.

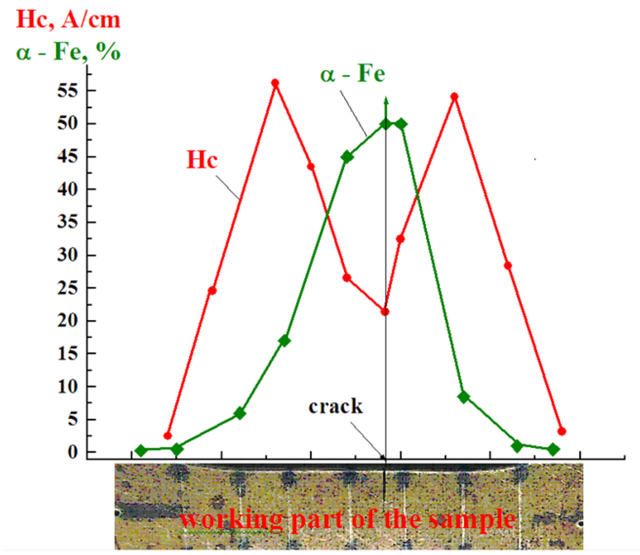


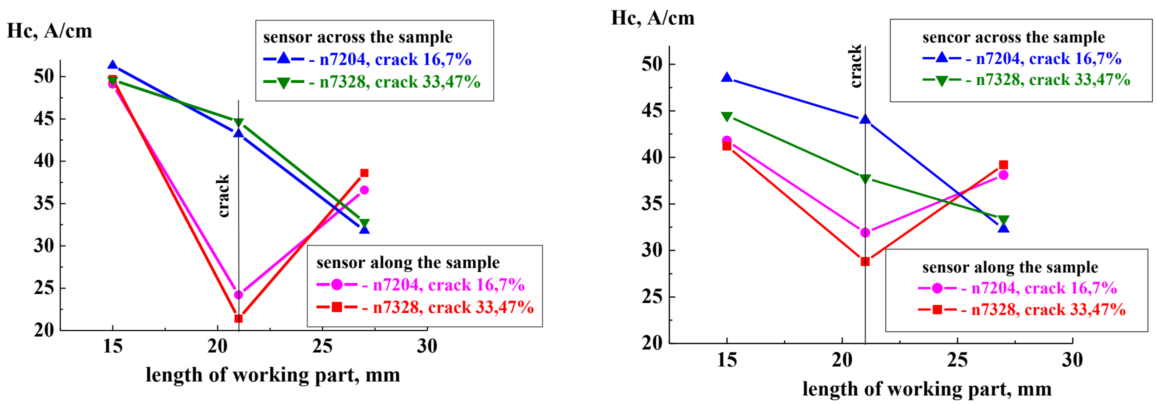
Figure 13. Distribution of the ferromagnetic phase (α-Fe) volume and the coercivity of the Ns on the working length of the specimen after the sign-variable cyclic strain before the fracture with the amplitude of the elasto-plastic strain $\varepsilon_a = \pm 0{,}5\%$

It follows from the obtained data, that the number of the sign-variable strain cycles being increased as well as under tension (see Fig.7), the increase of the coercive force value occurs caused by the intensive elasto-plastic strain till the metal rigidity failure. After that its values decrease caused by the decrease of the magnetic properties at the increase of the cracks number and size under the less intensive elasto-plastic strain. Here, the continuous growth of the ferromagnetic phase (α-Fe) volume occurs up to the fracture. Thus, taking advantage of the coercive control method it was managed to determine, that the structural changes of the metal, assessed by the change of the ferromagnetic phase (α-Fe) volume, do not show the damages accumulation processes proper enough.

As under the cyclic strain the values of the coercive force depend on the direction of the sensor magnets shoe poles location relatively the direction of the applied loading (see Fig.12 a, b), the application of the structurescope with the sensor D12 for the conventional structures makes possible to determine the direction of the main stresses and to reveal the fatigue crack initiation. In Fig.14 the data of the force *Hc* values in the crack zone and the threshold areas after the cyclic run (the strain amplitude $\varepsilon_a = \pm 0{,}4\%$) till the cycles number n=7204 (the crack square being of 16,7% of the nominal) and n=7328 (the crack square being 33,4% of the nominal) when the fatigue crack is located in the middle between the sensor magnets shoe poles (in the crack zone) and in the distance of 6mm from the sensor centre in all directions from the crack (the crack threshold area) from the external (a) and internal (b) surfaces of the specimen, when the sensor magnets shoe poles are located along and across the specimen working area are presented. The sensor magnets shoe poles being located along the external surface of the working area of the specimen (along the direction of the loading application, that is, perpendicular to the crack direction), there are sufficiently smaller values of the coercive force relatively the the periphery zones, which makes possible to reveal them. It should be noted, that on the internal surface of the specimen from pipe, where the crack are not available, the decrease of the coercive force values occurs just over the crack itself, when the sensor magnets shoe poles are located along the working area of the specimen (Fig.14 b). It testifies the possibility to reveal the under-surface cracks by the sensor of not deep magnetization D12 of the decreased base of measurement. When the sensor magnets shoe poles are located across both the external and internal working area of the specimen, the coercive force does not respond to the available crack.

Thus, the obtained experimental results testified sufficient differences of the ferromagnetic steel 05кп and austenitic (paramagnetic in its initial stage) steel AISI 304 in respond to the change of the coercive force values under the mechanical loading and unloading. Under the static and cyclic tension of the laboratory specimens from steel 05кп and AISI 304 the maximum values of the coercive force differ in almost one order.

The ferromagnetic steel 05kp tends to increase by 50% the coercive force values in the unloaded state than in that loaded one, for the steel AISI 304 such respond being not available.



а) *б)*

Figure 14. The coercive force value on the external (a) and internal (b) surfaces of the specimen at the position of the sensor magnets shoe poles along and across the working part of the specimen (at n = 7204 and n = 7328 the number of cycles)

Application of the structurescope makes possible to separate the damages accumulation under tension or cyclic sign-variable strain on the crack initiation stage, caused by the elasto-plastic strain, and the stage of the crack development, caused by the metal rigidity failure (including pore formation). The paper in question did not deal with the damage accumulation nature at the crack initiation and crack development stages. To study the physical nature of the damages accumulation some metallographic investigations are expected to be carried out.

The developed method of the coercive-metric control can be widely applied, foremost, for the engineering health monitoring of the structural elements from the austenitic steels, and after the corresponding investigations have been completed, for the ferromagnetic steels in the nuclear power-engineering, aircraft and space engineering, chemical industry, etc.

Conclusion.

1. Experimental interpreting of the possibility to evaluate the damage degree of the investigated steels according to the coercive force value taking into account its kinetics under the static and cyclic loading, was carried out.

2. Sufficient differences of the ferromagnetic steel 05кр and the austenitic (paramagnetic in its initial state) steel AISI 304 coercive force respond to the unloading under the mechanical loadings, have been determined.

3. The residual strength of the metal can be evaluated according to the coercive force values on the raising or dropping areas of the *Hc* kinetics curves under tension or cyclic sign-variable strain.

4. Taking advantage of the structurescope made possible to determine the stage-by-stage nature of the damages accumulation processes under the static or cyclic loadings: the growth of the coercive force values corresponds to the elasto-plastic strain (the crack initiation stage), and their decrease is caused by the metal rigidity failure, when pores or cracks are initiated (the crack development stage).

5. The stage-by-stage damages accumulation according to the change of the coercive force kinetics direction after some run cycles number makes possible to build the curve of the irreversible damage (the French line type) and to evaluate the cyclic durability not according to the metal fatigue (fracture) curve, as it is assumed to be in engineering, but at the crack initiation stage, which greatly contributes to the destruction risks decrease.

6. The possibility to take advantage of the structurescope for the monitoring of the most loaded zones of the important structural elements for revealing the most deformed areas, when the directions of the main stresses are found, as well as the metal rigidity failures, when the pores and fatigue cracks are being initiated, has been shown. The sensors with the small-base measurement of the coercive force can reveal both the surface and under-surface cracks.

7. It was determined, that it is possible to adapt the coercive kinetics to the tension diagram, the deformation and the coercive force distribution along the working length of the laboratory specimen being built. Under the cyclic deformation it is possible to build the kinetics of the coercive force values distribution along the working length of the laboratory specimen according to the number of the loading cycles and to reveal the most damages zones, the fatigue cracks initiation and development being specified as well.

8. Under the tension or the cyclic sign-variable strain the increase of the coercive force values is caused by the elasto-plastic strain, and the decrease of the *Hc* values is caused by the fact, that the metal rigidity failure processes prevail over the deformation processes, caused by the change of the metal structure evaluated by the formation of the ferromagnetic phase (α-Fe) volume. The metal structure changes estimated by the change of the ferromagnetic phase (α-Fe) volume do not show the damages accumulation processes.

9. The obtained results can be the base for development of new approaches to the rapid evaluation of the residual life of the structures metal taking advantage of the simple non-destructive method.

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ОЦІНЮВАННЯ ПОШКОДЖЕНЬ МЕТАЛУ КОНСТРУКЦІЙ ПРИ СТАТИЧНОМУ ТА ЦИКЛІЧНОМУ НАВАНТАЖЕННІ ПО ВЕЛИЧИНІ КОЕРЦИТИВНОЇ СИЛИ

Олексій Гопкало[1]; Геннадій Безлюдько[2]; Володимир Нехотящий[3]

[1]Інститут проблем міцності імені Г.С.Писаренка НАН України, Київ, Україна
[2]ООО "Специальные научные разработки", Харків, Україна
[3]Інститут електрозваювання імені Є.О. Патона НАН України, Київ, Україна

Резюме. *Наведено результати експериментальних досліджень оцінювання ступеня пошкодження феромагнітної сталі 5кп та аустенітної (парамагнітної у початковому стані) сталі AISI 304 при статичному та циклічному навантаженні по величині коерцитивної сили (Нс). Встановлено стадійність процесів накопичення пошкоджень: зростання значень коерцитивної сили відповідає пружно-пластичному деформуванню (стадії зародження тріщини), а зниження їх значень пов'язане зі втратою суцільності металу при виникненні пор і тріщин (стадія розвитку тріщини). Встановлення стадійності накопичення пошкоджень по зміні напрямку кінетики коерцитивної сили після певного числа циклів напрацювання дозволяє побудувати криву незворотної пошкоджуваності (типу лінії Френча) і оцінювання циклічну довговічність не по кривій втоми (руйнуванню) металу, як прийнято в інженерній практиці, а на стадії зародження тріщин, що істотно знижує ризики руйнування. Отримані результати можуть стати основою для розроблення нових підходів до експресного оцінювання залишкового ресурсу металу конструкцій простим неруйнівним методом.*

Ключові слова: *структуроскоп, робоча частина зразка, коерцитивна сила, деформація, тріщини втоми, пошкодження.*

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