Diagnostics of damages in the pre-destruction zone during low-cycle loading in pipeline systems

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Abstract. The paper considers the methodology for determining the location of fatigue destruction using non-destructive testing methods, as well as the assessment of the residual resource. The metal of the main pipeline was tested to test the determination of the stress-deformed state. The main causes of the destruction of pipeline systems were investigated and the choice of non-destructive testing methods that were adequate in terms of the diagnostics of main pipelines was justified. The developed methodology for testing low-cycle fatigue of samples of main pipelines that were in operation allows us to establish regularities of change in the stress-deformed state and magnetic characteristics of the material of main pipelines at various stages of its life cycle. The iterative cyclic experimental studies carried out make it possible to determine the potential destruction zone and evaluate the effect of the number of cycles on the residual resource of the pipeline. Experimental data correlate with data obtained using a digital network-centric system.

1. Introduction
Currently, the volume of gas pumped through main pipelines is growing, and the strength reservation of the pipes used is reduced due to the aging of the pipeline. Increasingly, the responsibility lies with engineers who ensure trouble-free and rational operation of the gas pumping system.

During operation, main pipelines are affected by cyclically varying loads, they operate under unstable conditions, in fact, which leads to fatigue damage.

One of the more important factors of fatigue loading on main pipelines is the low-cycle effect.

In the presented paper, the behavior of the material was studied, cyclicity of the main pipelines, which is one of the main components of the strength assessment of the gas pumping system operability.

2. Failures, accidents and destruction on main pipelines
An analysis of the causes of accidents and failures on the linear part of the main pipelines showed that the main and most serious cause of emergency situations is the problem of stress corrosion. According to statistics, for this reason, most (up to 70%) accidents occur (figure 1). Of these, longitudinal stress corrosion cracking accounts for about 90%. Stress corrosion cracking according to the spatial orientation of the cracks is divided into longitudinal and transverse.
Stress corrosion cracking is the destruction of metallic materials as a result of the simultaneous durable exposure to static stress and a specific external environment. In the oil and gas industry, this term is used to describe the destruction of pipe metal, occurring through the slow propagation of cracks, during the long-term operation of pipelines. Typically, destruction of this kind arises on the outer surface of the pipe as a result of exposure to electrolytes, as well as external and internal stresses and variable environmental conditions that occur during operation of pipelines and pipe production [1-7].

When assessing the conformity of pipes, the classification of defects is used (table 1).

**Table 1.** Classification and types of defects in the linear part of the main pipeline

| Category of defects                          | Conditions of occurrence                           | Defect names                                                                 |
|---------------------------------------------|---------------------------------------------------|------------------------------------------------------------------------------|
| Surface defects of the main metal           | when rolling sheets                                | hairline, rolling captivity, ingot captivity, undercut, rolled crack, stress crack, scratch, sunset, risk, tears |
| Internal defects of the main metal          | during operation and storage of pipes and pipe fittings (SDT) | stress corrosion and corrosion and defects                                      |
| Internal defects in the manufacture of cast billets | in the manufacture of cast billets                  | scratches, undercuts, risks, nicks                                            |
| Defects in the geometry of pipes and pipe fittings | in the manufacture, loading, unloading, transportation, storage, installation and operation | hot crack, gas shell, cold crack, intercrystalline crack, metal inclusion, segregation, sieve shell, shrink shell, non-metallic inclusion, flocen. |
| Internal defects in factory welds          | in the manufacture of pipe blanks and pipe fittings | dent, ovality, curvature, corrugation                                          |
| Surface defects in factory welds           | in the manufacture of pipe blanks and pipe fittings | shells, lack of fusion (non-fusion), slag inclusions, pores, cracks, cracks, pores, fistulas in the weld, surface oxidation of the weld, shell, undercut of the fusion zone |

The most common types of defects in the piping of compressor stations are stress corrosion cracking that occurs in places where insulation coating and additional (non-design) stresses occur in pipes, in places of mechanical damage. Also, over time, the reliability and safety of operation of
compressor station equipment are reduced due to erosion and thinning of the walls, changes in the properties of materials over time, the appearance and development of local defects, and corrosion damage.

3. Destruction of main pipelines
Low-cycle destruction occurs with a significant number of pressure drops or an external load (from 100 to 10,000 cycles). This destruction is very characteristic for long-term operated main pipelines. The causes of low-cycle destruction are considered pressure drops, the presence of defects and damage, or stress concentrators. At present, about 53% of main pipelines have been in operation for more than 30 years, and the age of individual pipelines reaches 50-60 years [8].

Main pipeline systems operate in a quasistatic configuration mode of performance, as a result of which these objects are not evaluated from the point of view of accumulation of damage in the pipeline material and the period of safe operation is not regulated. However, recent studies demonstrate, in fact, that during the operation of main pipeline equipment in the material complex processes occur at the micro and macro levels, causing damage accumulation, which in local areas have every chance of reaching a maximum state, and in case of an emergency increase the risk of accidental destruction [9-11].

Consequently, steel technological pipelines and underground main pipes with long service lives contain obvious and hidden defects in the metal:

- macroscopic continuity defects such as cracks, corrosion damage, installation technological defects, etc. (linear dimensions - of the order of several millimeters);
- microcracks and structural inhomogeneities of the metal (linear dimensions - of the order of hundredths of a millimeter);
- zones of plastic deformation of the metal - areas with an increased stress-deformed state of the metal, etc.

Macroscopic continuity defects lead to a significant decrease in the strength properties of the metal of the steel pipeline, so they are dangerous and unacceptable.

Microcracks and structural heterogeneities of the metal, areas with increased metal SDS are also a potential danger to the strength of the metal. They create very favorable conditions for the nucleation of new and the growth of existing macroscopic metal continuity defects in operating equipment, and therefore should also be identified during the technical diagnosis of steel pipelines.

For the safe operation of the steel pipeline, steel pipes with the indicated metal defects must be repaired or removed from further operation.

Macroscopic continuity defects such as cracks and corrosion damage to metal of steel pipes can be detected by physical methods of non-destructive testing, using visual measuring control and technical means of defectoscopy (x-ray, ultrasound, magnetic, eddy current, etc.).

However, defects in the fine structure of the metal of steel pipes — microcracks and structural inhomogeneities of the metal, zones of plastic deformation of the metal, and concentration of mechanical stresses — cannot be detected by existing detection techniques, since they are not sensitive to this type of metal defects.

Defects in the fine structure and the stress state of the steel pipe metal can be reliably detected by physical methods and technical means of non-destructive testing of metal SDS.

In real time, there are all kinds of methods and technical methods for non-destructive testing of the stress-deformed state of metal of iron products and constructions, based on various physical principles, which have their own pros and cons. The analysis demonstrates, in fact, that magnetic and electrical methods and technical methods for controlling the stress-deformed state of metal of iron products and constructions based on the correlation of structurally sensitive magnetic characteristics of the metal with the value of mechanical stress are more effective in field work [12-16].
Thus, in order to obtain reliable information about the technical condition of steel pipelines, it is important to identify macroscopic defects in the continuity of the metal, as well as control the SDS of the metal.

It should be noted that during the operation of main pipelines, the metal of the pipe is in a complex (flat, volumetric) stress state, which was formed due to the force action of a large number of factors (pressure inside the pipe, external design and unaccounted loads, residual mechanical stresses of the metal).

Therefore, the assessment of the capabilities of technical means of non-destructive testing to assess the current state of the metal of steel pipes of the main pipelines, based only on the results of laboratory studies, seems clearly insufficient.

The most optimal way to assess the potential capabilities of methods and technical tools for assessing the SDS of metal in steel pipes can be through complex cyclic testing of samples made from steel pipes cut from a long-running main pipeline.

4. Loads of the main pipelines
The pipeline during operation experiences loads and impacts, which, in the general case, are spatio-temporal functions. Therefore, considering the duration of pipeline service life and the high variability of loads and impacts, initial information about loads and impacts should be prepared taking into account the time factor.

There are standard and non-standard conditions of the pipeline. In the first case, to calculate the parameters of the designed pipeline, a basic simplified procedure for the study and calculation of the stress-deformed state of the pipeline is carried out. For non-standard working conditions, an extended procedure should be applied to analyze the loads and impacts on the pipeline and calculate the stress-deformed state.

Non-standard conditions are those under which the laying of the pipeline route is planned for territories with the following characteristic features:

- wetlands and flooded areas;
- territories with subsurface voids of various origin (undermined territories in areas of mine construction, territories with karst voids, etc.);
- zones of permafrost;
- landslide zones;
- earthquake zones.

The list of special zones is open. At the choice of the designer, it can be supplemented with new positions. The loads and impacts on the pipeline are divided into two groups: functional and natural-climatic.

5. Object of study
The main pipeline is a complex connection of pipeline constructions that accept a large number of external influences, the main of which is internal pressure. When designing pipelines, main loads are taken into account, such as weight of pipelines, internal pressure, temperature effects and the effects of uneven soil deformations. However, during operation, the pipelines additionally experience static and cyclic loads, which lead to an accelerated production of the pipeline resource.

Thus, the assessment of SDS and the determination of the most loaded sections of pipelines is an important engineering task that must be addressed throughout the entire period of operation to ensure the safety and performance of pipelines.

As an object of research, a part of the main pipeline of DN 1200 and 1400 mm with a working pressure of up to 7.5 MPa, which worked for more than 30 years, was chosen. 10 samples were made.
Considering the long service life of the main pipeline to assess the real state of the physicomechanical properties of the metal of steel pipes, a series of tests of standard samples made from these pipes was organized.

Based on the analysis of the data provided by the dispatching service of Gazprom Transgaz Ufa LLC, the actual working gas pressure in the main pipeline for the working period ranged from 0 MPa to 7.5 MPa. Considering that the maximum working pressure for which the steel pipeline is designed corresponds to $P_{\text{max}} = 7.5$ MPa, the upper limit of the pressure interval during cyclic testing of the bench was taken to be $P_{\text{max}}$. Thus, the deflection at the test bench was 0.2 mm.

According to the test results, the samples withstood a different number of cycles: samples from a pipe of DN 1200 mm withstood from 49,000 to 53,500 cycles, and from a pipe of DN 1,400 mm pipe from 36,500 to 38,000 cycles.

6. Results of the testing

Based on the measurement results, graphs of the tangential and normal intensity of a constant magnetic field are constructed. Also the graphs of the resulting magnetic field intensity was constructed. The abscissa axis is the length of the working zone of the sample in mm, and the ordinate axis is the magnetic field intensity in A / m. The obtained graphs for sample No. 1 from a pipe DN 1200 mm are presented in figures 2-4.

![Figure 2](image1.png)

**Figure 2.** The resulting intensity of the constant magnetic field along the length of the working zone along the upper side of the sample No. 1 from a pipe DN 1200 mm.

![Figure 3](image2.png)

**Figure 3.** The resulting intensity of the constant magnetic field along the length of the working zone along the upper side of the sample No. 1 from the pipe DN 1400 mm.
Figure 4. The drop in the resulting intensity of a constant magnetic field along the length of the sample No. 1, No. 2 DN 1200 mm.

7. Conclusion
In the process of the performed work, the impact of low-cycle fatigue on main pipelines is considered. As an object of research, main pipelines sections with a diameter of 1200 and 1400 mm that were in operation for 30 years were selected.

According to the measurements made using the IKN-2M-8 device, regularities of changes in the SDS and magnetic characteristics of the material of the main pipelines at various stages of its life cycle were established. The graphs show that the drop in the resulting intensity of a constant magnetic field along the length of the sample on all samples has a similar structure: after the first 2 measurements, the graph goes up, then the values are almost unchanged. According to measurements after 70% of the resource of the samples, a jump in the considered parameter occurs.

Thus, we obtained the results of a comprehensive study of the parameters of the physicomechanical characteristics of the main pipeline samples, taking into account the actual life and the nature of cyclic loads using a stress concentration meter - up to 30% of the maximum number of cycles, fluctuations in values, then steady-state values and jumps in readings start at 70%.

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