Change of Acoustic and Magnetic Properties of Metals of Main Pipelines under the Influence of Cyclic Loads

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Abstract. Today, the assessment of the technical condition of objects taking into account the effects of variable loads is gaining popularity in the world. As a rule, such loads do not lead to simultaneous destruction of structures. Such facilities include trunk pipelines. The variable loads arising in them are determined by the technological mode of operation. For main pipelines, a low-cycle load is characteristic, for gas pipelines, a multi-cycle load. During cyclic impact on the metal, its slight damage occurs at the micro level, which is almost impossible to detect without special diagnostic methods. Microdamage in the metal accumulates in the form of microcracks and, with an increase in the number of loading cycles, the number of microcracks increases several times, which can ultimately cause macroracks and lead to design failure. When analyzing accidents that occurred on pipelines, the fact that failure occurred without the presence of characteristic crack-like defects in the pipe wall is often noted. Thus, fatigue damage to the metal is a dangerous factor that can lead to the destruction of pipelines. Given the new trends in diagnostics, one of the key issues is the assessment of damage to prevent accidents on main pipelines. The article considers the study of the dependence of the acoustic and magnetic properties of specimens from 09G2S steel loaded in the equivalent mode of the main gas pipeline, depending on the level of accumulated damage.

1. Introduction
Currently, when analyzing structures and their elements, more and more attention is focused not on the problem of determining the stress-strain state, but on solving a more General problem – the problem of determining the resource of structures [1]. One of the main questions that must be answered when solving this problem is the question of formulating the conditions for failure of structural elements and, as a result, methods for investigating the onset of the specified state of the product. Traditionally, when analyzing the resource of structures and their elements under the influence of mechanical loads, there are two types of limit state: the destruction of the structure and the appearance of a defect in the structure of a given size [2, 3]. The study of the conditions for the occurrence of such failures is associated with the description of the destruction process in the structure. To date, two main approaches to solving this problem are being developed in numerical methods for solving problems of deformable solid mechanics [4]. The first approach is to solve related problems, i.e. problems in which the development of defects leads to changes in the properties of the material and/or geometry of the structure being studied [5]. The second approach is to assess the degree of damage to the material in the structural elements, provided that the defects and their growth are not explicitly considered. The first approach is divided into two main directions: direction A, based on continuous damage...
mechanics [6], in which defects are not explicitly introduced, but damage accumulation measures are introduced, and their relationship to the degradation of the material properties of the structure is set [6, 7]; and direction B, based on fracture mechanics [8], in which the development of defects (pores, cracks, etc.) is modeled taking into account changes in the boundary conditions in the considered structural element and the re-arrangement of the grid when the defect size changes [9, 10].

The second approach does not allow us to explicitly assess the moment of structural failure, but allows us to get a clear picture of the degree of damage to the structure based on the models used for damage accumulation. This pattern can be used when evaluating the design resource. This approach meets the requirements for methods of studying destruction processes in mass systems of finite element analysis used in solving engineering problems.

2. Cyclic testing of samples
In previous works [11, 12], we have considered the causes of cyclic loads in main pipelines, as well as mathematical models that can be used to describe the resulting stress fluctuations in the pipeline walls.

The model of gas pressure fluctuations in the main gas pipeline was chosen as a mathematical model for fatigue testing [13, 14, 15]. The level of active ring stresses in the pipe wall was taken as the considered parameter. The equation of oscillations:

\[
\sigma = 31.3 \cdot \sin (0.00037 \cdot t) + 3.13 \cdot \sin (0.0063 \cdot t) + 202.7
\]

Samples of the form shown in figure 1 were used as test samples. The actual sample is shown in figure 2.

![Figure 1. Drawing of samples for cyclic tests.](image1)

![Figure 2. 09G2S steel sample photo.](image2)

Tests were carried out in accordance with GOST 25.502-79. [16] Metal samples are made of steel 09G2S. Sample thickness is 4 mm, surface roughness Rz = 40. This brand of steel is very common for pipelines in use. Also, steel 09G2S is quite similar in properties to steel grades 17GS, 10G2, 10G2B and others, which allows it to be used as an analog for fatigue tests for other oil and gas pipelines [17].

3. Simplifying equations for cyclic testing
As a simplification, equation (1) is reduced to the equation of a simple sine wave. The main dependence was assumed to be the difference in ring stresses in the pipe metal, since they have the greatest amplitude.

Thus, this type of loading will have the following parameters:

\[
\begin{align*}
\sigma_{\text{MAX}} &= 237 \text{ MPa}; \\
\sigma_{\text{MIN}} &= 168.4 \text{ MPa}; \\
A &= 68.6 \text{ MPa}.
\end{align*}
\]

T= 17000 s.
Since the mechanical properties of the metal allow cyclical testing at frequencies exceeding the required thousands of times, the oscillation period for testing can be reduced from 17,000 s to 1.7 s. Due to this property, the test time can be significantly reduced [18].

The resulting number of cycles can later be used to determine the relative damage to the material, expressed in fractions of one, which is defined as the quotient of the current number of cycles to the number of cycles before the plastic deformation of the samples.

4. Fatigue testing

The test cycle shown in Fig. 4. According to this cycle, the sample is not loaded at the initial moment of time, and the value of the stresses in it is assumed to be zero. After the test starts, the sample is loaded to the maximum stresses that occur in the pipeline wall. After this, the force value is reduced to the value corresponding to the minimum value of the ring stresses. The first sample was tested until a crack appeared in the working area of the sample, 5-10% of the width of the working area (0.5 – 1 mm). The size of the crack was determined using an optical method. After that, 2 more samples were tested in the same way to determine the average number of cycles.

![Figure 3. Cyclic loading model for fatigue testing.](image)

Table 1. Determination of the number of cycles before destruction of samples.

| Number of sample | Number of cycles before the crack appears |
|------------------|------------------------------------------|
| 1                | 22736                                    |
| 2                | 22621                                    |
| 3                | 22683                                    |

According to the results of tests of 3 samples, the average number of cycles leading to the appearance of a fatigue macro-crack in the metal was obtained-22680.

Since the fatigue process includes several stages [19], which take place at different scale levels in the construction material [20, 21], consideration of which cannot be carried out when evaluating the fatigue resistance of the structure, it is convenient to enter some dimensionless value that characterizes the level of accumulated damage in the construction material. This value is called the damage measure $\phi$. This value can take values from the segment $[0, 1]$. In this case, the value $\phi = 0$ corresponds to the case when there is no damage, i.e. a completely new design, and the value $\phi = 1$ corresponds to the level of damage at which fatigue macro-damage occurs in the structure.

To assess changes in metal properties at the later stages of pipeline operation, samples were tested to simulate the condition at damage levels $\phi$ 0.5, 0.75 and 0.9. at a value of $\phi = 0.6$, the metal damage was estimated for a service life of approximately 10 years, which is currently one of the most common periods of pipe operation. Large damage values are modeled for pipelines with a service period of 20 years or more.
5. Ultrasonic and magnetic examination of loaded samples

After the fatigue tests, acoustic parameters were measured for each sample. Measurements were made in the working area of the samples.

If we start from the fact that the majority of gas and oil pipelines are currently diagnosed using in-line diagnostic projectiles, then the most satisfying diagnostic methods should be applied in in-line projectiles. Such diagnostic methods are acoustic and magnetic control methods.

5.1. Ultrasound examination of samples

The ultrasonic flaw detector USD3-50 was used for measurements. The device allows you to conduct echo, echo-shadow and mirror-shadow methods of ultrasonic control, determine the coordinates of defects, the speed of passage of ultrasonic waves through the medium, etc.

Data on the speed of ultrasonic waves were obtained by a direct method (the speed of the passage of waves was displayed on the screen of the flaw detector) using the echo method of ultrasonic control.

Ultrasound velocity measurements were made over the entire working area of the samples on both sides.

| The level of fatigue damage accumulation, \( \varphi \) | Average speed of longitudinal ultrasonic waves in the material |
|--------------------------------------------------|---------------------------------------------------------------|
| 0                                                | 5983                                                          |
| 0.5                                              | 5977                                                          |
| 0.75                                             | 5975                                                          |
| 0.89                                             | 5973                                                          |
| 1                                                | 5971                                                          |

Based on the obtained data, the dependence of the speed of passage of ultrasonic waves on the level of accumulation of fatigue damage was plotted.

![Figure 4. Dependence of the velocity of longitudinal ultrasonic waves on the amount of accumulated fatigue damage.](image)

\[ y = -1.3407x^2 + 10.22x + 5982.9 \\
R^2 = 0.9921 \]

5.2. Measuring the range of the gradient of the magnetic field strength of samples

The measurement of the range of the gradient of the magnetic field intensity was carried out by a direct method using a defectoscope of the ferrosonde DF-201.1 a gradiometer.

The principle of operation of flaw detectors is based on converting the intensity or gradient of the constant magnetic field at the measurement point using a ferrosonde Converter (polemer or...
gradiometer) into an electrical signal proportional to the value of the intensity or gradient of the magnetic field. The electrical signal taken from the output of the Converter is amplified and processed, the result is observed on the display. The display shows the measured values and information.

**Table 3. Magnetic diagnostics data samples.**

| The level of fatigue damage accumulation, $\phi$ | Number of sample | 1     | 2     | 3     | Average |
|------------------------------------------------|------------------|-------|-------|-------|---------|
| 0                                               |                  | 5932  | 5881  | 5907  | 5907    |
| 0.5                                             |                  | 1420  | 1397  | 1382  | 1400    |
| 0.75                                            |                  | 1082  | 1061  | 1118  | 1087    |
| 0.89                                            |                  | 997   | 1030  | 1008  | 1087    |
| 1                                               |                  | 981   | 965   | 972   | 973     |

Based on the obtained data, a graph of the dependence of the magnetic field gradient span on the accumulated fatigue damage was plotted.

**Figure 5.** Dependence of the magnitude of the gradient of the magnetic field intensity on the amount of accumulated fatigue damage.

6. **Conclusion**

As can be seen from the graphs in Fig. 4 and Fig. 5, with an increase in accumulated damage, changes in the properties of the metal occur: a decrease in the speed of passage of ultrasonic waves and a decrease in the scope of the gradient of the magnetic field intensity. These changes are caused by damage to metal crystals, the occurrence of various dislocations and clusters that prevent the passage of ultrasound through the metal. The nature of the nonlinear dependencies obtained from the test results correlates well with images of samples cut from pipelines that have been in operation for various amounts of time. For these samples with a small amount of operating time, individual localized cracks of small size are characteristic, which cannot significantly affect the change in acoustic and magnetic parameters. With increasing operating time and, as a result, the number of cycles, the number of cracks begins to increase sharply, many of them form large networks. Such large damages lead to changes in the parameters of the steel.

Thus, when conducting in-line diagnostics of main pipelines, it is necessary to pay attention not only to finding defects in the pipe wall, but also to measure the values of acoustic and magnetic parameters. After performing cyclic tests in the mode corresponding to the operating mode of the pipeline, it becomes possible to create an additional method for evaluating the technical condition, taking into account the impact of cyclic and periodic loads. It is thus possible to improve the reliability of pipeline systems, to reduce the risk of accidents and increase the accuracy of forecasting of a
residual resource of pipelines.

7. References

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