Restoration of the Serviceability of Defective Sections of Oil and Gas Pipelines Using the Magnetic-Pulse Method

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Abstract. The analysis of emergency situations on the main pipelines is presented, as a result of which it was found that the occurrence of fatigue microcracks and their growth under load is one of the main causes of accidents, which indicates the danger of defects of this type and the need to eliminate them at an early stage. The article discusses a method for healing fatigue cracks in oil and gas pipelines using magnetic pulse processing of metals MPP. The composition of the magnetic-pulse unit MPU and the principle of its operation are described in detail. The principle of operation of this method is based on the induction of eddy currents in the processed metal using a magnetic-pulse unit MPU. The induced currents cause thermo-mechanical processes in the vicinity of the cracks, which lead to the closing of the edges of the cracks and the prevention of their growth. The tests were carried out using two groups of samples from steel 17G1S. One of them was processed by magnetic pulse. Then both groups were tested for impact strength. The test results showed a significant increase in toughness for samples processed with magnetic pulse compared to unprocessed samples.

1. Introduction
The main gas and oil pipelines are in a complex stressed state, being subjected to significant variable loads both from the inside and from the outside, which over time leads to fatigue of the pipe metal, accumulation of damage, deterioration of physical and mechanical characteristics, and ultimately to destruction pipeline walls.

Based on this, the assessment of the strength of pipelines during long-term operation, restoration of the pipelines' operability, and extension of the residual resource are an actual question.

Analysis of the results of diagnostic examinations and investigation of the causes of accidents at oil and gas facilities shows that the most dangerous defects are fatigue cracks [1-3].

The danger of this type of defects lies in the fact that they cause stress concentration at their tips, mainly hoop stresses from the internal pressure of the stored or transported product [4-7], and as a consequence, under load stress cracks can grow rapidly and pass into a critical stage immediately after formation, which will eventually lead to the destruction of the metal [8-9].

In this regard, early detection of these defects, their elimination and prevention of their further growth can reduce economic losses from accidents, as well as reduce labor costs for repair and restoration work.
Today, there are a number of methods for restoring defective pipeline sections. The choice of repair method or combination of methods used is determined by many factors, including nature, position, the orientation of defects, expected repair accuracy, tools availability, steel grade, product thickness, and experience required [10 - 11].

Only recently have researchers confirmed the possibility of eliminating cracks and preventing their growth using short high-density current pulses [12-15].

The researchers suggest that under the action of a high-energy pulsed current, compressive stresses arise in the vicinity of the cracks, which work on bringing the edges of cracks closer to each other and closing them [16-17]. Simultaneously, local heating occurs at the tips of the cracks, leading to the melting of the tips of the cracks and the termination of their propagation [18-20].

This work considers the issue of the possibility of healing fatigue micro cracks in highly loaded metals using magnetic pulse processing (MPP).

2. Analysis of emergency situations on main gas and oil pipelines associated with the propagation of fatigue cracks

Analysis of destruction and damage of pipeline transport structures during their long-term operation and determining their causes allows to reduce their consequences, and increase the reliability of pipelines by taking measures aimed at reducing the causes of accidents and preventing them occurrence.

The work [21] provides an analysis of the accident at one section of the main gas pipeline of the Republic of Sakha (Yakutia) (2008).

The accident was the destruction of the main valve of the Christmas tree, which had been in operation for more than 20 years at the time of the accident.

The failure occurred in the area of transition from the valve body to the flange connection, the view of the valve fracture is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Fracture of the Christmas tree valve.

Studies of the destroyed valve showed that the accident occurred as a result of the formation of fatigue microcracks and their development during long-term operation, which led to a brittle fracture of the metal.
In paper [22], a study of the causes of accidental destruction on a gas pipeline made of a spiral-seam pipe with a diameter of 377 mm and a wall thickness of 6 mm was carried out. At the time of destruction, the pipe had been in operation for more than 25 years. During the study of the destroyed sections of the pipeline, it was established that the formation of a crack began from the base metal of the pipe body, the growth extended along the tube body and the weld border, and the welding boundary.

Also, the study identified a short fracture section of 45 mm in length with a thickness (5 mm) less than that of the adjacent sections, which may indicate a greater degree of plastic deformation that preceded the failure.

Researchers have suggested that this part is the focus of destruction, from which fatigue microcracks were formed initially, then, during long-term operation, extended in both directions from the source in the longitudinal direction. Figure 2. shows a general view of the fracture of the gas pipeline wall.

In paper [23], hydraulic tests were carried out on pipes with a diameter of 1220 mm, made of steel 17G1S, containing fatigue microdefects (average diameter 10-15 microns). As a result, it was found that in the defective area, the strength of the metal is reduced by 20% compared to the intact part of the tube.

In addition to the above, many studies of the physical and mechanical state of structures in the oil and gas industry during long-term operation have shown the danger of fatigue microcracks and their high ability to rapidly grow under load and pass into a critical stage, which will eventually lead to the destruction of the metal [24-26].

Based on the foregoing, timely detection and elimination of fatigue cracks before they reach a critical stage is an urgent task.

Figure 2. General view of the fracture of the gas pipeline wall.
3. Materials and methods

3.1. Principle of operation of the magnetic pulse processing of metals
The principle of operation of this method is based on the induction of eddy currents (Foucault currents) in the processed metal. It is known that electric currents do not pass through cracks, they choose a path in which the resistance is minimal. Accordingly, the current lines accumulate near the crack tip, which leads to a local increase in the current density in their vicinity (Fig. 3).

![Figure 3. Increase in current density at the crack tip.](image)

Large gradients of the electric field in the vicinity of cracks cause thermal and mechanical processes, which are expressed in the form of heating of the crack tip and compressive stresses on the crack edges [27,29].

Based on the above, the purpose of the magnetic-pulse treatment of defective sections of pipelines is to heal fatigue cracks at the initial stage of their development and to prevent their further propagation.

Healing of cracks occurs as a result of two processes: heating of the crack tip and the formation of a drop of molten metal; closure of crack edges under the action of compressive stresses (Fig. 4).

![Figure 4. Thermal and mechanical processes under the influence of MPP: (a) Heating at the crack tip; (b) compressive forces.](image)
3.2. Composition of the magnetic-pulse unit MPU

MPU principle of operation is based on the method of direct conversion of electric energy stored in ES batteries to an electromagnetic field formed in an inductor at the discharge of pulse batteries of the energy store. The electromagnetic field of the inductor induces eddy currents in a preform of the processed part. Inductor’s electromagnetic field interaction with currents in the preform produces deformation work and causes pulse heating of the part [30-32].

The magnetic impulse unit MIU consists of an energy storage ES, which includes high-voltage pulse capacitors and vacuum or gas arresters, a charger containing a high-voltage transformer and a rectifier, and a conductor made of a material with high electrical conductivity and high mechanical strength. [33-34]

Pulse capacitors are charged to a predetermined energy level using a charger that converts AC (220V) into high voltage DC. Then, the stored energy in the capacitors is discharged in the inductor using a block of discharges. The discharge process has a single and instantaneous character. During the discharge of the NE, a pulse current with an amplitude of 10 ... 200 kA, duration 10 ... 1000 μs flows in the inductor, depending on the level of stored energy and the parameters of the working inductor [35].

The conductor converts the electrical energy flowing in it into an electromagnetic field. Figure 5. shows the functional diagram of the magnetic-pulse unit MPU-3KJ

![Functional diagram of the MPU-3KJ](image)

**Figure 5.** functional diagram of the MPU-3KJ.

3.3. Test equipment, samples and research methodology

During the study, the samples were tested for impact toughness, since it is this method that is most sensitive to changes in the structure, the presence of defects, residual stresses, etc.

As a material for testing, were used six samples of 17G1S steel (0,15−0,20 C; 0,4−0,6 Si; 1,15−1,6 Mn; ≤0,3 Cr; ≤0,3 Cu; ≤0,035 P; ≤0,04 S; ≤0,008 N; ≤0,08 As, вес. %), Which is used to manufacture pipes for main pipelines.

A notch with a fatigue crack with a radius of 0.1 mm was made on the surface of the samples using a ZDM-200 machine (Fig 6.).

![Test sample](image)

**Figure 6.** The test sample.
The tests were carried out using a pendulum-testing machine of the German company RKP-300 with maximum impact energy of 300 J, at room temperature in accordance with GOST 9454-78.

Two samples were immediately tested for impact toughness, the rest of the samples, using the magnetic-pulse unit MPU-3KJ, were pulsed with different characteristics and directivity vectors, and then tested for impact toughness.

Figure 7. shows the magnetic-pulse unit MPU-3KJ

![Figure 7. Magnetic-pulse unit MPU-3KJ.](image)

Figure 8. shows the inductors used in the tests

![Figure 8. Inductors.](image)

The characteristics of the magnetic pulse upon exposure to the samples are presented in Table 1.

| № sample | The direction of magnetic action on crack | Stored energy, kJ | Impulse current, kA |
|----------|-----------------------------------------|-------------------|---------------------|
| 1        | along the crack                          | 2                 | 41                  |
| 2        | across crack                             | 2                 | 84                  |
| 3        | along the crack                          | 3                 | 62.9                |
| 4        | across crack                             | 3                 | 125                 |

4. Results
The results of testing samples for impact strength are presented in table 2. The calculation of the impact strength is made by the following formula:

\[ a_k = \frac{A_k}{F} \]  

(1)
Where $a_K$ - the impact toughness of the specimen; $F$ - the cross-section area of the specimen in the notch location before the test ($cm^2$); $A_k$ - the energy absorbed in destruction is equal to the fracture energy (joule).

| № sample | The direction of magnetic action on crack | $A_k$, joule | $F$, $cm^2$ | $a_K$, $J/cm^2$ |
|----------|----------------------------------------|--------------|-------------|----------------|
| 1        | along the crack                         | 46,20        | 0,823       | 56             |
| 2        | across crack                            | 54,73        | 0,842       | 65             |
| 3        | along the crack                         | 50,40        | 0,812       | 62             |
| 4        | across crack                            | 64,38        | 0,882       | 73             |
| 5        | without magnetic impulse action         | 32,8         | 0,848       | 38,67          |
| 6        | without magnetic impulse action         | 33,3         | 0,861       | 38,67          |

Table 2. The result of calculating the impact strength for samples from steel 17G1S.

After the completion of all types of experimental work, the surface of the cross-section of the samples, along which the destruction occurred, was studied using a microanalyzer in the mode of a scanning electron microscope (resolution 100 Å, accelerating voltage from 1 to 100 Å KV). The obtained images make it possible to say that the surface of the crack after magnetic pulse processing hardened and become more solid.

Figure 9 shows structural changes in the form of metal hardening.

![Figure 9](image)

5. Discussions
The obtained test results, which are presented in table 2, show a clear improvement in the strength properties of the processed samples with magnetic pulse action since the impact toughness of the processed samples increased by 40-60% compared to samples that were not subjected to magnetic pulse action.

To this day, there is no clear definition of the limits of the energy required for the healing of microcracks. In addition, the influence of the size and distribution of microdefects on the required energy level is not studied enough. According to our results, the greatest increase in the impact toughness of the samples was achieved when exposed to a magnetic pulse with an energy of 3 kJ and an Impulse current of 125 kA.
Microstructural images of metal fracture show that the surface of the crack after magnetic pulse processing hardened and became more solid. It means that the mechanical energy of the pendulum-testing machine, in this case, is spent not only on the complete destruction of the sample itself but also on the destruction of the more hardened fatigue crack surface.

6. Conclusion
Research into the causes of accidents at oil and gas facilities has established that accidents due to the occurrence of fatigue microcracks and their growth are widespread. This indicates the danger of this type of defect and the need to eliminate defects of this type at an early stage of their growth.

The tests were carried out using two groups of samples from steel 17G1S. One of them was processed by magnetic pulse processing. Then both groups were tested for impact strength. The test result showed a significant increase in toughness for samples processed with magnetic pulse compared to unprocessed samples.

As a result of the tests, the samples processed with magnetic pulse showed better resistance to destruction. Based on this, it can be concluded that the magnetic-pulse processing of metals has great prospects in the restoration of defective pipeline sections containing fatigue cracks, and can be used to extend the residual life of the pipeline and reduce the likelihood of emergency situations.

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