Analysis of the reasons for the accelerated failure of oil pipelines in the regions of the Far North and Siberia

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Abstract. From about the time trends of development of oil gas complex of the country requires reassess the reliability and durability of pipelines for various purposes. The reason for this trend is the gradual displacement of the producing provinces towards regions with extremely low climatic temperatures, difficult natural conditions, and highly aggressive components of the oil production. Analysis of the reasons for the accelerated destruction of pipes in the northern regions of the country made it possible to identify two main causes of failure. This is the development of corrosion-mechanical defects and insufficient cold resistance and crack resistance of materials at low climatic temperatures. The paper analyzes the role of non-metallic inclusions in increased defectiveness of steel X70 pipes, an analysis of the influence of the microstructure and non-metallic inclusions of operation the pipes in cold climate.

1 Introduction

The key task of the Russian fuel and energy complex is the construction of infrastructure and the development of hydrocarbon production centers in northern latitudes and permafrost areas. The main criterion for making a decision on the implementation and determination of the operability of oil and gas infrastructure equipment is a set of low-temperature physical and mechanical properties of the metal. In connection with the tightening of operating conditions, as well as an increase in the number of aggressive external factors, the provision of a set of mechanical properties, and, accordingly, the operational reliability of equipment, is becoming an increasingly difficult task. Decreased operating temperatures are becoming a key external factor, typical for all northern regions. Thus, an important task is to ensure the required properties of steels at low temperatures and to predict the operational reliability of equipment [1-3].

Analysis of the causes of destruction and damage of oil pipelines operating for a long time in the northern and northeastern regions of the country and research by other authors [4-6] suggests that the main reason for the decrease in their performance is the occurrence and development of brittle crack-like defects that occur, including in the areas of corrosion damage to the metal.

The main factor determining the increased damageability of metal and welded joints of pipes is the superposition of several phenomena simultaneously acting on the pipe metal - the presence of corrosive non-metallic inclusions in the structure of steels [7-11], the nucleation in these zones of corrosion defects leading to the development of brittle cracks from them. Low temperature operation climatic pipes of wires in wintertime further reduced metal pipe fracture and lead to increased incidence of accidental destruction and whether at stated failures.

As a rule, non-metallic inclusions of metallurgical origin are “hard” barriers along the path of motion of dislocations and contribute to the localization of stresses in the matrix. These stresses can exceed the ultimate strength of the matrix and lead to its local destruction [8, 9].

An increase in the degree of non-equilibrium of the matrix, for example, banding and uneven graininess of the microstructure, and the formation of corrosion defects increase the likelihood of microcrack initiation. The destruction of the matrix near the inclusion can be represented as a consequence of two competing processes: the accumulation of internal stresses during deformation due to the inhibition of the motion of crystal structure defects and their plastic relaxation. A decrease in the temperature of the metal slows down the relaxation processes, further increasing the likelihood of the development of a brittle crack [12-14].

The goal of this study is to carry out experimental studies of pipes after operation during 25-41 thousand hours in pipelines located in the northern and northeastern regions.

2 Materials and methods

Samples (coils) from pipes that worked 25-41 thousand hours in pipelines. The cutouts were marked from 1 – 8 from. The material of all investigated pipes is steel X65-X70, table 1.

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Table 1. Chemical composition.

Mass., %									
C	Si	Mn	Cr	Ni	Cu	Al	V	S	P
0,09-0,12	0,15-0,35	1,55-1,75	≤0,3	≤0,3	≤0,3	0,02-0,05	0,09-0,12	<0,03	<0,03

The cutting of templates and further blanks for samples for testing and research was carried out on a band sawing machine with forced cooling in order to prevent elevated temperatures in the cut area, entailing changes in the initial structural state.

To determine the level of operability of the pipe metal in conditions of low climatic temperatures, the impact toughness (KCV) at a temperature up to –60 °C according standart GOST 9454-78and crack resistance (CTOD) were studied according ASTM E1290.

Determination of quantity of nonmetallic inclusions carried out by means of optical microskopy according. The determination of the styichiometric composition of inclusions was carried out by X-ray diffraction method. The phase composition was deciphered using the ICDD powder diffraction database (PDF-2).

Corrosion properties were carried out in accordance with the requirements of the standards:

– ASTM G3, G5, G59, G102 for determination of the corrosion rate in deaerated 5% NaCl and solutions 5% NaCl saturated with CO_2;

– NACE Standard TM-0177 (method B) to evaluate Sulfide Stress Cracking (SSC) Resistance.

Sulfide stress cracking (SSC) was assessed in on plate specimens in Test Solution A for 720 hours. Prior to testing, the specimens were subjected to a static bend load at four points in the clamping device and the test stress was 90% of the yield strength. The samples installed in the clamps were placed in a test vessel, then the solution was deaerated and saturated with hydrogen sulfide, the concentration of hydrogen sulfide was maintained constant - not less than 2300 mg/L. At the end of the test period, the samples were removed from the test vessel, unloaded, washed, and checked for cracks.

3 Results

The impact toughness at a temperature of minus 60 °C and crack resistance results are given in Table 2.

As can be seen from the data, the impact toughness of pipe cuttings differs by more than three times, crack resistance - by more than nine times for studied samples. Such a difference in the stock of properties of the same steel arch, smelted according to the same regulatory and technical requirements, affect the low temperature reliability.

Table 2. Impact toughness and crack tip opening displacement at low temperatures.

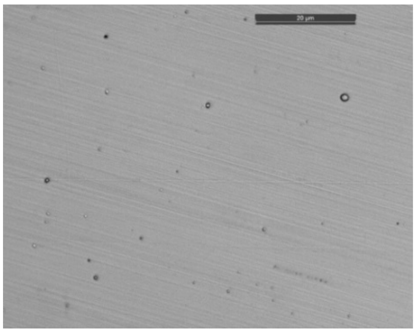
№	NMI*, %	KCV	CTOD min, δ_c	
		J/cm^2	mm	
		Temperature,^{0}C		
		-60	-10	-20
1	480	102	0,21	0,19
2	410	141	0,52	0,33
3	370	191	0.56	0,50
4	210	159	0,46	0,39
5	100	316	0,79	0,78
6	105	295	0,79	0,73
7	175	242	0,57	0,48
8	540	98	0,10	0,09

* Note: NMI * - the number of non-metallic inclusions in the section (1x1 mm) in percentage with respect to the steel of pipe No. 5, in which their minimum content was recorded.

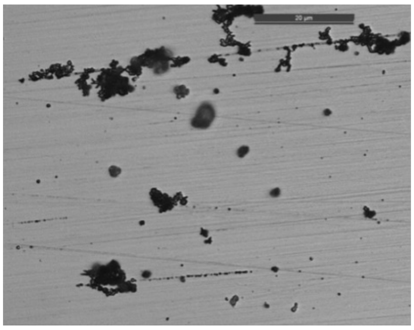
Metallographic studies of samples showed that the metal of all pipes is contaminated with non-metallic inclusions - Fig. 1, but their size and number is various. The maximum number of inclusions (number of pipes according to the degree of reduction in the number) is recorded in the metal of pipes No. 8, 1, 2, 3, and the minimum is noted in pipes No. 6 and 5. Table 2 shows the ratios of the content of non-metallic inclusions in the metal of pipes, regarding their number in the metal of pipe No. 5. It was found that non-metallic inclusions in the metal of all pipes are evenly distributed over the area of the thin section and have a generally rounded shape. The average size of inclusions is in the range from 1.5 - 2 to 5-15 microns, however, inclusions with average sizes from 30-40 microns (pipe No. 8) to 20 microns were found in pipe materials 8, 1, 2 and 3 - pipe No. 3. According to fracture mechanics, a critical stress must be reached at the crack formation point, determined by the Griffith-Orowan equation [15]:

$$\sigma_t \geq \sqrt{2E\gamma ef/\pi(1-\nu 2)L} \quad (1)$$

where E - Young's modulus; ν - Poisson's ratio γ_{ef} – effective surface energy (including the energy of plastic deformation).



a



b

Fig. 1. Non-metallic inclusions in pipe No. 5 (a) and pipe No. 8 (b).

For a heterogeneous material such as pipe metal, parameter L represents the size of the largest defect. For non-metallic inclusions to serve as nuclei of a critical crack, they must have an effective size exceeding L. In this study to definitions of effective size of the inclusions not intended, however, based on the data on the crack resistance of the metal pipe (at –20 °C), Table 1. Level of fracture toughness at minus 20 °C with δ_c = 0,09 mm (pipe No. 8) to 0,39 mm (pipe No. 4) is achieved by reducing the size of inclusions from 40 to 20 microns; and up to δ_c = 0,50 mm and more (pipes No. 3,7,6,5) in the absence of inclusions with dimensions greater than 15 microns.

Based on the results of the analysis, it was found that the phase composition of all steels, mainly consists of α-Fe, Fe_3C and inclusions based on calcium compounds - CaS, CaO. During the studies, it was found that the revealed inclusions are complex compounds based on the Al-Ca-Mg-O and Ca-Al-S-O systems. The presence of Mg in all analyzed inclusions indicates the exogenous nature of their origin. It was also found that niobium, introduced to inhibit grain growth during hot rolling, is mainly found in complex non-metallic inclusions such as Al-Ca-Mg-O and Ca-Al-S-O. For pipes with a low level of viscous properties (for example, pipes No. 8 and No. 1) the share of niobium in complex inclusions reaches 100%, for pipes No. 5 and 6 is about 50% of the amount introduced into the steel. It was shown that the higher the proportion of niobium in these inclusions, the higher the uneven grain and banding of the steel structure, the lower its low-temperature impact toughness and crack resistance. Niobium unbound in complex non-metallic compounds is present in steel in the form of individual carbonitride particles with sizes from 0,5 to 1,5 microns.

The structural state of steel determines not only its mechanical properties, but also its resistance to the development of corrosion defects. In this work, the corrosion assessment was made of the effect of the microstructure of the metal of pipes on the resistance to the development of corrosion defects.

The calculation of corrosion rates, carried out in accordance with the standards G 59 and G 102, showed (Table 3) that the metal of pipes with the maximum unevenness of the structure (uneven grain size, banding, number and size of non-metallic inclusions) has the highest corrosion rate, reducing of non-equilibrium state the rate of corrosion of the pipe metal decreases.

Table 3. Corrosion rates of the studied pipes.

Pipe №	Media	Corrosion rate, mm/year	Media	Corrosion rate, mm/year
8	5% NaCl	0,19	5%NaCl + CO_2	0,78
2		0,17		0,67
7		0,14		0,61
5		0,14		0,58

Results show pipe 5 that has the lowest corrosion rate in both solutions that is also correlate with the lowest quantity of inclusion. Sample 8 have the largest number of inclusions and the highest corrosion rates.

Sulfur is one of the most common elements in oil fluids, therefore, evaluating the performance of pipe materials without analyzing their resistance to sulfide cracking would be incorrect.

It was found that no cracks were found on any of the samples after testing. However, on the surfaces of pipe samples from No. 8 to No. 3 with large non-metallic inclusions, blisters were found that located in places where large non-metallic inclusions were found, table 4 and Fig. 2.

Table 4. The number of blisters on the surface of the samples after testing for sulfide cracking and large – more than 10 μm non-metallic inclusions in the pipe broom.

№	Number of NMI units/mm^2	Number of blisters, units/mm^2
1	4	9
2	4	3-5
3	2	2
4	2	3
5	0	0
6	0	0
7	1	0
8	6	10-12

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a

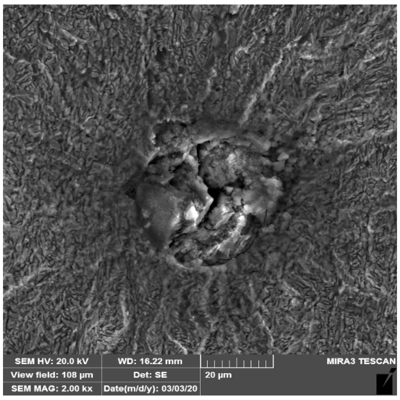

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Fig. 2. Samples 8 after sulfide cracking tests (a) blister locations - after removing the sediment layer (b) Non-metallic Ca-Al-S-O inclusion under the sediment layer (swelling).

In Fig. 2(b), it is clearly seen that the interface between the inclusion and the matrix is etched, and microcracks are visible in the body of the inclusion itself. The set of etched boundaries and microcracks of inclusion, in the course of further operation, can initiate the development of a brittle crack-like defect and lead to accelerated destruction of the pipe.

4 Conclusions

1. Analysis of damaged pipes shown that the reasons for the accelerated failure of oil pipelines in the northern regions of the Russian Federation are insufficient cold resistance and corrosion resistance of the pipe metal associated with the superposition of several jointly acting risk factors. These include the disequilibrium of the structure (graininess, banding and the presence of large corrosive non-metallic inclusions). Non-metallic inclusions act as stress concentrators, impeding movement of dislocations affect the strength and fracture the material. Also, large non-metallic inclusions and corrosive damage zones arising around them provoke the formation and development of brittle cracks.

2. Impact toughness test determined that the low-temperature toughness of the base metal of pipes depends on the level of unevenness of the microstructure of steel and differs by more than three times, and crack resistance (CTOD min) already at minus 20 °C - more than nine time. Corrosion resistance of steel also depends on the non-equilibrium of its structure - the corrosion rate of the pipe metal with the maximum structural heterogeneity is 0,78 mm / year, with the minimum – 0,58 mm / year.

3. The distribution of non-metallic inclusions in the metal structure of all pipes is uniform, the shape of the inclusions is generally round, the average size of the inclusions does not exceed 10-15 microns. The inclusions are complex compounds of the Al-Ca-Mg-O and Ca-Al-S-O type. In a number of pipes, for example, No. 8, individual inclusions up to 40 μm were found.

4. Large non-metallic inclusions have a significant effect on the corrosion resistance of pipe materials under conditions of sulfide stress cracking resistance tests. Although the materials of all pipes did not show a tendency to sulfide cracking, although blisters were found at the locations of large non-metallic inclusions on the surface of some test specimens.

5. The conducted research has established that at low temperatures of testing the metal of pipes, the stability of low-temperature mechanical properties and crack resistance is not fully ensured. The fixed scatter of values leads to the danger of reducing the reliability of pipelines during operation under conditions of their operation in regions with low climatic temperatures and requires the development of additional methods and volumes of control of the metal of pipes supplied for the construction of oil pipelines in the northern regions of the country.

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