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On Metal Status Monitoring Issues of Continuous Operation Pipelines

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Abstract. The paper shows the relevance of the mechanical properties control of the metal of pipes and welded joints when estimating the safety of pipelines based on the results of periodic inspections. Old pipelines remain in operation in the system, but the issues of aging and degradation of the metal of the pipe and there welded joints remain without proper attention. By aging of a metal, the authors mean a gradual transition to a more stable energy state. How quickly change occurs depends on many factors. Thus, the very mode of operation of the main oil and gas pipelines contributes to the aging of the pipe metal. In addition to strain aging, there are other mechanisms for changing the mechanical properties of pipelines, for example, stress corrosion. Currently, half of all destruction on main gas pipelines occurs due to stress corrosion, the article shows the mechanism of stress corrosion. The paper contains an analysis of the aging and degradation mechanisms of pipe metal. Moreover, not only directions of development of metal control methods are shown but also have taken close look into aging and degradation during the long-term operation of pipelines.

1. Introduction

As you know, the danger of defects on main pipelines should be determined by the type and size of the defect, the acting stresses (operating, residual, temperature, from external influences and soil processes), the influence of the environment, as well as the mechanical properties of the metal in the defect areas. Upon detailed consideration, each of the listed factors has unsolved problems that do not allow achieving high accuracy in assessing the strength and residual life of pipelines with detected defects. Here we will consider some of the problems in terms of control of the properties of metal pipes and welded joints. Pipes are made of low-carbon low-alloy steels, which must meet certain requirements for strength (ensure high operating pressures), for plasticity (prevent damage from accidental impacts, scratches), impact strength (avoid avalanche damage). For that purposes with the use of well-known both with new technologies they achieve a certain composition and structure of the metal, which ensures high strength. This is how new steel grades appear, which are used in the construction of new pipelines, such as Eastern Siberia - Pacific Ocean (ESPO), Power of Siberia, Turkish Stream, Nord Stream. The system also retains old pipelines in operation, in which pipe steels of the first generations were used, and the reliability of which is currently in doubt, since in assessing their safety and resource, the issues of aging and degradation of themselves are still neglected metal pipes and their welded joints. Aging of a metal means a gradual transition to a more stable energy state. For example, in steels with a ferrite-pearlite structure, ferrite grains are always supersaturated



with impurity carbon and nitrogen atoms, which impede the movement of dislocations, thereby providing high strength. Over time, especially under conditions conducive to an increase in the mobility of atoms, impurity atoms move to the grain boundaries and participate in the formation of iron carbides and nitrides. So in ferrite grains strength decreases and plasticity increases, and at grain boundaries hardness increases and brittleness appears. In addition, dislocations are either neutralized or also go to the grain boundaries, thereby the crystal structure passes into a more stable state. As a result, all the properties of the metal gradually change: How quickly change occurs depends on many factors. One of them is temperature. With an increase in temperature, the mobility of impurities and dislocations increases, they more easily overcome potential barriers and aging accelerates (the term thermal aging is known). The second factor is the cyclic (re-static) mode of pipeline operation. During the moments of regime switching, new dislocations are generated at macro- and micro-stress concentrators. These new dislocations in their motion entail clouds of impurity atoms (Cottrell clouds). Thus, the very mode of operation of oil and gas pipelines contributes to the aging of the pipe metal. The chemical composition of the steels is an important factor. Obviously, the type of the crystal structure of steel is determined by iron atoms. All other atoms (impurities and alloying elements) are involved in creating defects in the crystal structure. Some of them are fixed in the nodes of the lattice, others are in the interstices. And all of them have an impact on the mobility of dislocations, and therefore, on the dynamics of structural changes during long-term operation. Modern steels used in the construction of new pipelines are distinguished by their high fineness. This is achieved by special technologies for rolling and heat treatment of sheets. In fine-grained steels, the grain boundaries are much larger than in coarse-grained ones. Since any boundary between the grains of the crystal structure is an obstacle to dislocation, it is easy to understand that fine-grained steels are high-strength. However, there is also a nuisance here - the smaller the grain size, the easier it is for impurity atoms from the depths of the grains to reach the boundaries, which determines the aging rate. This issue has not yet been adequately studied, but there is a danger that new pipelines, built from some new steel grades, will age at a faster rate.

2. Extra mechanisms changing mechanical properties of pipelines

In addition to strain aging, there are other mechanisms for changing the mechanical properties of pipelines, for example, stress corrosion [1, 2]. At present, half of all destruction on main gas pipelines occurs due to stress corrosion [3-5] (this phenomenon has different definitions in different industries; the term "stress corrosion cracking" - SCC is used on main gas pipelines). In our opinion, supported by observations and experiments, stress corrosion is associated with the saturation of the metal with hydrogen. Hydrogen penetrates into the metal in the form of atoms (more precisely, in the form of nuclei of hydrogen atoms, i.e. in the form of slow protons) formed on the metal surface. Atomic hydrogen can be formed as a result of

- 1) bio-corrosion,
- 2) chemical reactions with the participation of hydrogen sulfide contained in the pumped product,
- 3) the reduction of hydrogen cations from groundwater under the influence of the negative potential of the pipe induced by the electrochemical protection system.

Hydrogen, penetrating into the pipe metal, participates in the formation of gas molecules of hydrogen (H_2), methane (CH_4), ammonia (NH_3), which are collected in intergranular microspores of the crystal structure [6-8]. This leads to a gradual steady increase in internal stresses, in the future - to cracking of the metal and destruction of the pipeline. Microstructural studies show that during stress corrosion, decarburization and grain growth are observed, which fits into the general theory.

Probably, there are other mechanisms of pipeline metal degradation during long-term operation. For example, a mechanochemical effect [9] is known, which consists in the fact that in zones of concentration of mechanical stresses, local electrochemical corrosion is significantly accelerated. This is explained by the fact that high mechanical stresses shift the electrochemical potential of the metal and accelerate the electrochemical dissolution of the metal. This phenomenon can be observed during the development of surface cracks, which were formed by the mechanism of stress corrosion, and then

the mechanochemical effect was “connected”, which led to the deepening of the crack by dissolving the metal at the crack tip.

The study of the laws of aging and degradation of metal is important both from the point of view of assessing the reliability of old pipelines, and for the development of effective control methods.

Thanks to the research of a number of scientific centers [10, 11], it is known that during deformation aging the following changes occur: tensile strength, yield strength, hardness increase, relative elongation and contraction decrease when specimens are stretched, impact toughness and crack resistance decrease. Integrally, all these changes negatively affect the reliability of pipelines, therefore, it is accepted to consider a complex change in properties as degradation.

3. Determination of mechanical properties of pipe's metal

Currently, the following methods are used to determine the mechanical properties of pipe metal in relation to the tasks of assessing the state of pipelines based on the results of periodic inspections or when investigating emergency situations.

1) Based on the steel grade and relevant documents (standards, certificates, projects). However, these documents define only the lower limits of properties at the time of delivery of pipes, and to a large extent, the actual properties may differ significantly. This approach does not take into account the scatter of mechanical properties that is always present within the same batch of pipes, and even in the same pipe at different sections. And most importantly, aging and degradation of the metal during long-term operation is not taken into account. Moreover, degradation processes proceed faster precisely in the defective pipe sections. Therefore, an assessment of a defect without taking into account the degradation of the metal can lead to an incorrect result, when there is no safety margin at all.

2). Cut and test samples from the emergency stock of pipes [12-17]. But this approach also has disadvantages. Firstly, during long-term operation of pipelines, there may no longer be an emergency stock from the same batch of pipes. Secondly, pipes in the emergency stock also age, albeit at a slower rate. In addition, the spread of properties within the batch of pipes has not gone anywhere.

3). It is often possible to cut samples directly from an operating pipeline, for example, after another failure or during repair with replacement of pipes. This approach is better than the previous ones, but it does not exhaust all the problems. The metal properties of the cut and tested samples may differ from the properties of the metal in the defect zone, the hazard of which must be assessed.

four). The hardness testing method is sometimes used. Comparing the hardness of the metal on the tested samples and in the area of the detected defect on the pipe, you can get some idea of the state of the metal at the defect. But this method does not differ in accuracy, therefore it is used as a preliminary method, which must be supplemented with other research methods. Thus, practically all known methods of metal control on an operating pipeline have one or another disadvantage.

4. Prediction of a reliability of a pipeline

In the tasks of predicting the reliability of pipelines, it is required to determine the intensity of changes in all important mechanical properties of the metal. For this, at least, it is necessary to compare the state of the same metal in the same area at the beginning of operation and at the moment, after a significant period of operation. This task, at first glance, seems insurmountable. But this is only at first glance. Having studied the general laws of the phenomenon, by combining the efforts of specialists in different fields (mechanics, physicists, instrumentists), it is possible and necessary to solve this problem. And there are ideas here.

1). Use the method of metal restoration to its original state by means of special thermomechanical processing of samples cut from the pipeline. This approach was developed in the Chelyabinsk school of pipe makers [10]. In this case, it is considered that after reduction, the metal acquires the same mechanical properties as in the state of delivery of pipes from the manufacturer. The method is interesting, but there is a risk of incorrectly defining the recovery mode. Additional fundamental research is required.

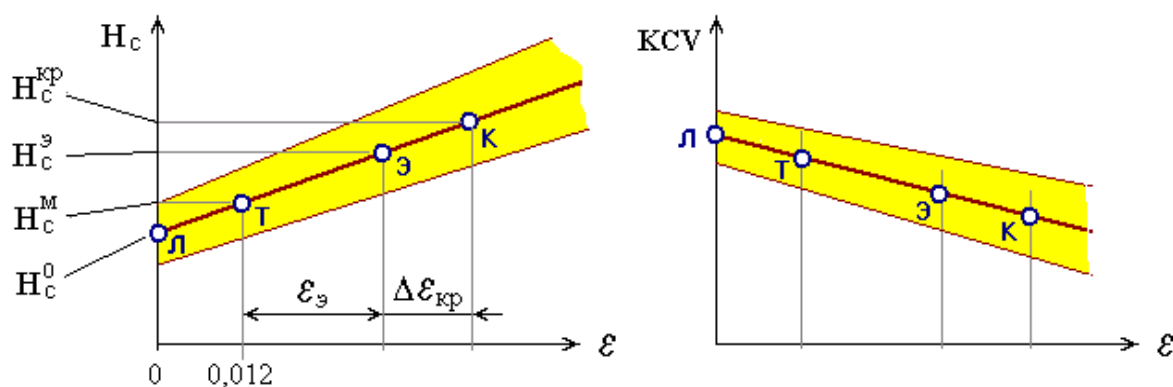
2). To study the dynamics of changes in the metal of the pipeline, starting from this moment for some time ahead. Changes are achieved by special cyclic testing of samples, thereby simulating further operation. Then the obtained dependence is extrapolated back to the beginning of operation, and forward until the stock is exhausted at least one of the characteristics of the metal. Studies show [11] that over time, impact strength reaches its lower permissible level earlier than others.

3). The study of the laws of aging and degradation with the simultaneous observation of changes in various physical properties, allows you to find a correlation between the mechanical characteristics of the metal and its physical properties. In various scientific schools, magnetic, electrical, acoustic properties were used, and interesting relationships were established, for example, between coercive force and impact toughness (Fig. 1).

4). Use internal friction of the metal [18]. Internal friction is based on the dissipation of the energy of vibrational movements due to the irreversible transformation of the mechanical energy of the body itself or its constituent elements (up to molecules) into heat.

The analogy of the method of internal friction with the method of optical spectral analysis of materials and substances can be noted. In the case of spectral analysis, we obtain the frequency-energy spectra of absorption or emission of photons in matter. In the spectrum, each line corresponds to the energy of transition of certain electrons in certain atoms from one energy level to another. For each type of atom, there is a certain set of lines - "imprint". The presence of such an "imprint" in the optical spectrum determines the presence of a given type of atoms in the material under study.

In the method of internal friction, maxima also appear - peaks similar to lines in the spectrum. These maxima correspond to the transitions of individual metal elements (impurity atoms, dislocations, grain boundaries) to certain positions that differ in the energy level. By decoding these peaks on the curves of internal friction, in many cases it is possible to determine which processes occur in the crystal and with the participation of which defects. The only problem is that the transition energies in crystals depend on a large number of factors: temperature, method of exposure to the sample, vibration frequency, registration method, presence and concentration of impurities and alloying elements, crystal type. However, not all dependencies and characteristics have been studied. This is the main obstacle to the widespread use of the internal friction method in practice. Nevertheless, this method has great possibilities and prospects, similar to spectral analysis.



L - the state of the sheet, T - the state of the new pipe, E - in a state of operation for 50 years, K - critical state when KCV reaches the lower allowable value.

Figure 1. The relationship between the accumulated deformations, the coercive force H_c and the impact toughness KCV , obtained for the metal of the pipes of the Bukhara-Ural main gas pipeline.

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