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Method of the Mechanical Properties Evaluation of Polyethylene Gas Pipelines with Portable Hardness Testers

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Abstract: This article is devoted to the study of means and methods for non-destructive testing mechanical properties of polyethylene gas pipelines that have been in operation for 25–55 years. In order to assess mechanical properties, stress at yield was chosen as a key parameter. Stress at yield is determined from the results of tensile tests and is associated with the limiting circumferential (hoop) stress, determined from the results of tests for short-term pressure. Tensile tests require sample cutting and the shutdown of pipelines' service. To solve this problem of nondestructive testing of pipelines, tests were carried out using the methods of Shore, Leeb and dynamic instrumental indentation. According to the test results, it was revealed that the correlation coefficient between the values of stress at yield and hardness, obtained by the method of dynamic instrumental indentation, is 0.98 which confirms the possibility of the evaluation of the mechanical properties of pipelines by the method of dynamic instrumental indentation.

Keywords: polyethylene gas pipelines; polyethylene pipelines; hardness; dynamic instrumented indentation

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1. Introduction

Transportation of natural gas, oil and other liquid and gaseous products is carried out through pipelines of various types [1–3]. Polyethylene pipes are widely used for natural gas transportation in regional gas distribution systems. The construction of polyethylene (PE) gas pipelines was started more than 60 years ago, and the first PE gas pipelines in the Russian Federation were built more than 55 years ago. At present, their total length is more than 300 thousand km.

PE pipes have significant advantages over steel pipes when transporting gas. This applies to the ease of manufacturing and cost of pipeline construction, operational parameters, as well as reliability and durability [4–6]. PE pipes, unlike steel [7–9], are not exposed to internal and external corrosion. The world's experience in the operation of PE gas pipelines has confirmed their high reliability in a variety of conditions [10–12], including the impact of catastrophic earthquakes [13].

At the same time, with all the reliability and durability of the gas pipelines, they are exposed to various degradation processes occurring under the influence of ultraviolet radiation [14,15], as well as aggressive environments [16–18]. The first factor is excluded by the fact that all PE gas pipelines are laid underground. The transported natural gas has a low content of aggressive chemical elements. In this regard, the main harmful effects on the pipe material are associated with the chemical composition of soils and groundwater, as well as mechanical deformations of the soil [19,20]. In addition, it is well-known that, over many years of service, PE pipes are exposed to long-term changes in the structure of thermoplastics, leading to an increase in the degree of crystallinity and, as a consequence, an increase in the rigidity and brittleness of the material [21–23]. External influences and internal processes lead to changes of the pipe material's original properties over time.

Regulatory documents define the safe operation period of gas pipelines as 50 years. Currently, the length of gas pipelines that are older than 50 years in the Russian Federation amounts to tens of kilometers, but in the next decade this value will increase to tens of thousands kilometers. In this regard, the task of developing methods for technical diagnostics of gas pipelines with long service life and assessing their residual life is crucial [24,25].

Currently, there are a number of regulatory requirements for PE properties and pipes used for the construction of gas pipelines [26–28]. These requirements apply, among other things, to the physicochemical and mechanical properties. Determination of this parameters is carried out both on small-scale PE samples and on entire sections of pipes up to a meter in size or more. A common feature of all these requirements is that they apply to new pipes. Appropriate tests are carried out during the development of technological processes, as well as to confirm the quality of finished products. Currently, there are no regulatory documents to establish requirements and test methods for pipes that have been in long-term operation. The use of standard test procedure to assess mechanical properties of in-service pipelines has its flaws, such as:

1. Pipes that have been in operation for several decades do not meet modern requirements, which does not interfere with their safe operation;
2. The requirements for new pipes imply their resistance to various mechanical stresses during construction, while in-service pipelines do not experience such loads;
3. A complete list of tests of PE pipes implies the use of full-size samples, which, in the case of gas pipelines in operation, requires their complete shutdown in order to cut long sections of pipes (up to 10 m) with subsequent repair.

In summary, it is crucial to develop non-destructive methods for diagnosing the state of PE pipelines using small-scale samples. One of the key parameters characterizing the operational properties of a pipe is its mechanical properties, which provide resistance to internal gas pressure and strength under external influences [29]. In this research, the study of means and methods of non-destructive evaluation of PE pipes' mechanical properties is presented.

2. Materials and Methods

2.1. Samples

PE pipe samples were cut from both operating gas pipelines with 25–55 years of service and a new pipeline. A detailed description of the samples, as well as the results of a study of their physicochemical properties, are presented in [30]. The list of selected samples and their characteristics are given in Table 1.

Table 1. Samples and their characteristics.

Year of Construction	Service Life, Years	Diameter, mm	Wall Thickness, mm
1965	55	110	10.0
1972	48	160	9.1
1978	42	110	11.8
1982	38	110	10.0
1989	31	110	10.0
1996	24	110	11.0
2020	0	110	10.1

2.2. Standard Methods for Mechanical Testing of PE Pipes

The decrease in the performance of polymer pipes is characterized by the loss of the ability to resist plastic destruction and the occurrence of brittle fracture. Modern grades of polyethylene (for example, PE 100) had high long-term strength and a sufficient safety factor. Despite the development of safe and efficient materials for pipes of underground gas pipelines, diagnostics and monitoring of the condition of such gas pipelines are a very important task, especially the study of the mechanical properties of materials under conditions similar to operational conditions.

PE pipes' characteristics are fixed by the ISO 4437-1, where the main group is mechanical properties [26], such as:

- resistance to internal pressure [31];
- elongation at break [32];
- resistance to slow crack propagation [33];
- resistance to rapid crack propagation [34].

Tests to determine the resistance to internal pressure according to ISO 1167-1 [31] are used to assess the properties and service life of PE pipelines, their short-term and long-term strength characteristics. The result of a long-term pressure test suggests the presence of a transition point from ductile to brittle fracture along the time of thermal action [35].

Tensile tests are used to characterize the mechanical properties of a polymer in terms of modulus of elasticity, strength and elongation at break. The elongation at break is determined according to ISO 6259-1 [32] in tensile tests using a tensile testing machine.

An important indicator that determines the service life of PE gas pipelines is the ability of the material to resist crack propagation. During the processes of transportation, storage and installation, polyethylene pipes are at risk of damage. The characteristic of resistance to slow crack propagation determines the process of destruction of the material in the presence of a stress concentrator in the form of an initial defect. Resistance to rapid crack propagation characterizes the resistance of a pipe to point mechanical impacts with large stress gradients.

The considered standard methods for diagnosing the mechanical characteristics of gas pipelines involve testing of full-size samples. In this case, it becomes necessary to suspend the operation of the gas pipeline for a long time, which causes economic losses. Full-scale standard tests do not allow of assessing changes in the mechanical properties of PE pipes over time [36]. Therefore, it is proposed to consider the possibility of using small-scale tests to study the mechanical properties.

2.3. Non-Destructive Test Methods

Hardness measurement methods are the most common non-destructive tests to evaluate the mechanical properties of materials. Hardness measurements are often used to study the mechanical properties of polymers [37]. Since hardness testers are used in laboratory conditions (Brinell, Vickers, Rockwell) they are inapplicable for solving the tasks set, so portable hardness testers were chosen for the study [38]. In order to select the most suitable method for measuring hardness, tests were carried out using portable hardness testers of various hardness scales: Shore; Leeb and the dynamic instrumental indentation.

Shore hardness is the most commonly used method for testing the hardness of plastics. The standard [39] specifies a method for determining the hardness of plastics and ebonite by static indentation using two types of durometers: the type A durometer, used for testing softer plastics; and the type D durometer, for testing harder plastics. The Shore method is an empirical test designed primarily for quality control of plastics. To measure the hardness of samples by the Shore method, a hardness tester "NDTone TS" of type D was used [40].

The method of measuring hardness using Leeb scales is based on determining the ratio of the velocities of the impact body during the rebound and impact phases of the indentation process [41]. This method belongs to the dynamic methods of hardness measurements. Leeb hardness testers are widely used for technical diagnostics of the condition of various parts and structures [42–44].

A NDTone KT-C hardness tester with a Type C transducer were used to carry out measurements in this work, since it has the lowest impact energy of all standardized types of Leeb transducers [41,45].

The method of dynamic instrumental indentation (DII) [46] and its application to determine various mechanical properties of materials are considered in detail in [47]. There are works in which the DII method was used to study the elastoplastic properties of polymers [48,49].

In the present study, we used a device that implements the DII method similar to that described in [50]. Measurements were taken with a spherical indenter of 1.5-mm diameter and impact energy of 1.9 mJ.

3. Results

The stress at yield σ_y, determined from the results of tensile tests according to ISO 527-2 [51], was chosen as the main parameter characterizing the mechanical properties of PE. Type 1B test specimens were cut from each sample. Table 2 shows the average values of the test results for five test specimens for each pipe, as well as the calculated standard deviation (SD).

Table 2. Results of tests and measurements of PE pipes.

Sample	Service Life, Years	Short-Term Pressure Test	Tensile Tests		Hardness Measurements					
					Shore		Leeb		DII	
		Limiting Circumferential (Hoop) Stress, σ_c, MPa,	Stress at Yield, σ_y, MPa	SD, %	*HS*	SD, %	*HLC*	SD, %	H_{DII}	SD, %
20	0	24.2	23.2	1.7	73	1.8	633	0.7	163	2.2
96	24	18.7	17.3	1.7	66	3.2	616	0.9	135	6.7
89	31	24.0	20.8	1.0	71	3.8	624	1.3	149	3.3
82	38	25.4	23.8	0.4	69	4.5	618	0.6	157	1.8
78	42	10.6	20.0	1.1	56	5.5	571	2.1	89	4.5
72	48	27.1	23.5	0.4	64	3.9	607	0.8	168	3.0
65	55	25.5	22.1	1.8	72	3.1	629	0.4	164	1.2

As part of the study, tests for short term pressure in accordance with ISO 4437-3 [28] were also carried out. The results of the pressure at failure P_p were obtained, which were then recalculated into the limiting circumferential (hoop) stress in the pipe wall σ_c (Table 2) according to the equation:

$$\sigma_c = \frac{P_p(d_{em} - e_{min})}{e_{min}} \quad (1)$$

where P_p—pressure at failure, MPa; d_{em}—outer diameter of the pipe, mm; e_{min}—minimum measured pipe wall thickness, mm. This test was carried out once for each sample, since it requires a significant length of pipe. The type of fracture was also recorded; all samples were plastically fractured.

Tests according to the Shore, Leeb and DII methods were carried out directly on pipes without preliminary sample preparation. Several series of measurements were taken at five points on the surface of each pipe. The average value and corresponding standard deviation of hardness values are given in Table 2.

The results obtained from the experiment were analyzed:

– an assessment was made of the correspondence between the stress at yield, determined by tensile tests and limiting circumferential (hoop) stress, determined by the short-term pressure tests of full-size samples;
– the results of hardness measurements and stress at yield were compared by the value of standard deviation;
– the correlation coefficients between the values of hardness and stress at yield are calculated.

Comparison of the values of the stress at yield and limiting circumferential (hoop) stress is shown in the Figure 1. The standard deviation of the stress at yield values for different samples does not exceed 2% of the average value, which makes it possible to use it as a reference value. There is a good correlation between the result of a standard mechanical tensile test and the value of the limiting circumferential (hoop) stress, which characterizes the mechanical strength of the pipe under operating conditions. The limiting circumferential (hoop) stress in this experiment exceeds the stress at yield on average by 10%.

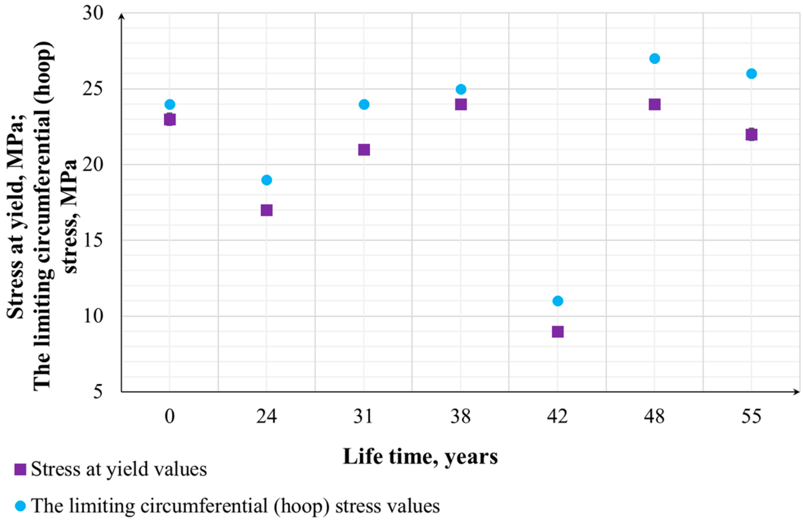


Figure 1. Results of mechanical tests.

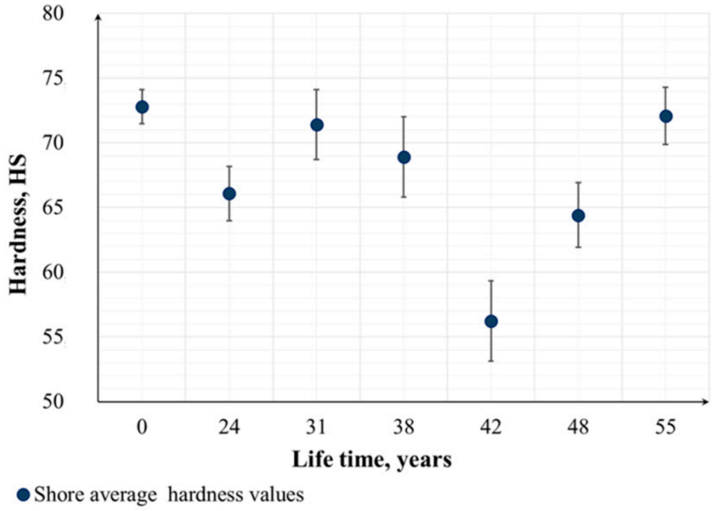
The results of hardness measurements are shown in Figure 2. Comparison of the dispersion of hardness measurements by different methods demonstrates the obvious advantage of the DII method. The values of the correlation coefficient between the values of the stress at yield and the hardness values according to the methods of Shore, Leeb and DII were 80%, 82% and 98%, respectively. Thus, it was concluded that the DII method is the most preferable for determining the yield stress of PE by a non-destructive methods.

To analyze the possibility of converting the hardness values according to the DII method (H_{DII}) into the values of the stress at yield (σ_y) the coefficient K was proposed. The K coefficient value is equal to the ratio of the stress at yield σ_y to the hardness values H_{DII} (Table 3). The sample from 1978 may be excluded from the analysis due to the large deviation of its properties from other samples. In that case, the average value of the K coefficient is 0.14, while the maximum deviation does not exceed 7%.

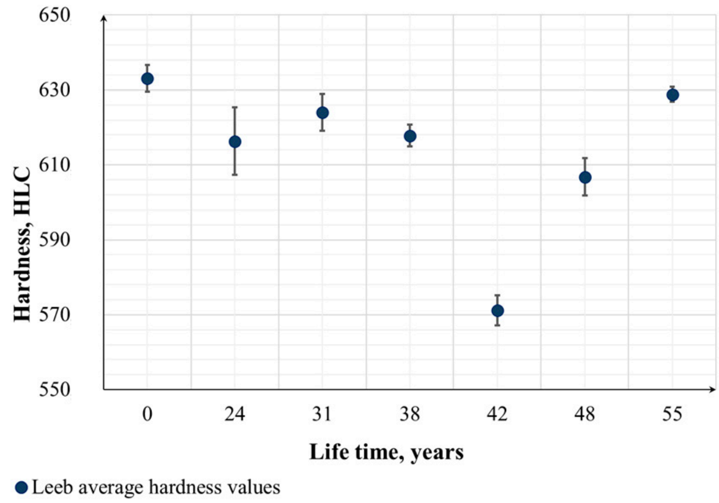
The method for measuring the stress at yield by the DII method should include the calibration of the hardness tester by determining the coefficient K, which is equal to the ratio of the yield strength σ_y to the hardness value H_{DII}, measured on one reference sample of the pipe. A new pipe can be taken as a reference sample, which eliminates the need to cut samples from existing pipelines.

Table 3. Values of K coefficient.

Sample	Years in Service	$\sigma_{y,\,MPa}$	H_{DII}	$K = \sigma_y/H_{DII}$
20	0	23	163	0.14
96	24	17	135	0.13
89	31	21	149	0.14
82	38	24	157	0.15
78	42	9	89	0.10
72	48	24	168	0.14
65	55	22	164	0.13



(**a**)



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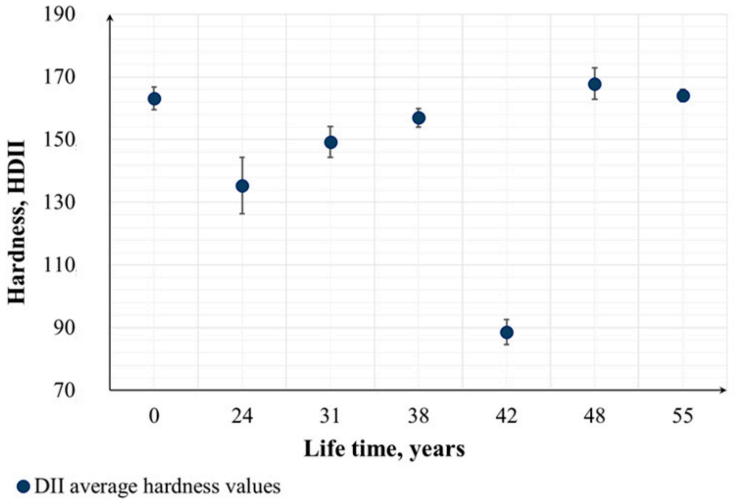

(**c**)

Figure 2. (**a**) Shore hardness test results; (**b**) Leeb C hardness test results; (**c**) DII hardness test results.

4. Discussion

The results obtained during this work made it possible to draw the following conclusions:

1. The values of stress at yield obtained during the tensile tests correlate well with the value of critical stress in the pipe wall determined during the short-term pressure tests;
2. The method of DII demonstrates the best results in comparison with Shore and Leeb hardness testers, both in terms of the spread of measurement results (random error) and in terms of correlation with the values of the stress at yield determined from the results of tensile tests;
3. The use of the DII method makes it possible to determine the stress at yield of the pipe material with high accuracy without cutting samples and stopping the operation of the gas pipeline.

5. Conclusions

The fact of a linear relationship between the yield stress and hardness of metals for static methods of measuring hardness is widely known. A similar relationship for thermoplastics has been much less studied. Measurements with a standard Shore hardness tester showed unsatisfactory results due to the large dispersion. Hardness values measured by dynamic methods (Leeb method) depend on the ratio of yield stress and modulus of elasticity. At the same time, the dynamic instrumental indentation method makes it possible to separately measure the elastic and plastic components of deformation, which determines its advantages over other methods. The study shows that the use of the DII method for evaluation of mechanical properties of polyethylene pipelines makes it possible to obtain results that have a slight random scatter and a high degree of correlation with the values of the stress at yield determined by tensile tests and limiting circumferential (hoop) stress, determined during the short-term pressure tests. The stress at yield of PE pipes of various grades and ages can be measured by the DII method by properly calibrating the instrument on a sample of PE pipe with a known value of stress at yield. Thus, the DII method can be effectively used for non-destructive testing of the technical condition of polyethylene pipelines in operation.

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