Comparative analysis of the use of epoxy and fluoroplastic polymer compositions as internal smooth coatings of the inner cavity of steel main gas pipelines

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Development of the oil and gas complex is inextricably linked with the improvement of transportation methods for extracted hydrocarbons. Use of internal internal smooth coatings is one of the ways to increase the efficiency of systems transporting natural gas. These coatings allow to reduce the cost of gas transportation and to protect additionally the inner pipe cavity from corrosion damage. Due to the trend of moving natural gas production to areas of the Far North with very low negative temperatures and an increased proportion of heavier hydrocarbon components in the transported gas, it is necessary to propose new technical solutions to ensure the efficient operation of main gas pipelines in new conditions. The authors propose to study the possibility of using a fluoroplastic coating that has not been previously used for gas pipelines and is considered as a promising one. This article presents a comparative analysis of the used epoxy coatings and promising fluoroplastic coatings applied to the surface of steel plates. The epoxy coating was applied to the surface of the plate which was cleaned by sandblasting, and before applying a fluoroplastic coating with low adhesive properties, the plate surface was prepared to ensure a strong adhesive bond by preliminary laser treatment and subsequent cold phosphatizing. In the course of the work, a complex of studies of the physical and mechanical characteristics of coatings was carried out, including determination of the impact strength of coatings at normal and negative temperatures, and determination of elasticity by the Erickson method, as well as determination of bending strength, and determination of equivalent roughness. According to the results of the research, it was revealed that the fluoroplastic coating has greater elasticity, bending strength and impact strength at low temperatures compared to the epoxy coating. In addition, it was found that fluoroplastic coatings are not inferior to epoxy coatings in terms of equivalent roughness, which affects the amount of hydraulic resistance. Thus, this work gives an idea of the relevance of using fluoroplastic coatings as internal smooth coatings to ensure more efficient operation of the gas pipelines in conditions of negative temperatures, with simultaneous increase of the proportion of heavier hydrocarbon components in the transported gas.
Key words: gas pipeline, fluoroplastic coating, epoxy coating, smooth coating, impact strength, coating elasticity, equivalent roughness coefficient.
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Introduction

At present time, large amount of natural gas reserves is developing of is planning for development in the Far North regions. So, for example, it is predicted that role of gas (consisting mainly of methane) will remain prevalent until 2035, when various deposits of Yamal and Kara sea shelf will be completely involved in operation [1]. At the same time, role of natural gas as an energy resource increases every year and its part in the global energetic balance rises [2], taking into account the part of developed mineral resources in the Far North [3]. Despite this tendency, qualitative changes with increase of the part of ethane-containing gas up to 50 % are predicted in the structure of gas reserves [4]. This gas is characterized by content of heavy hydrocarbons as well as non-hydrocarbon components with their part up to 12 % [5]. In this case, transportation of natural gas through main pipelines remains one of the main methods for gas delivery to customers. So, joint influence of the factors of extremal low temperatures in the Far North regions and increase of the part of heavy hydrocarbons and non-hydrocarbon components in the developed natural gas leads to necessity of improving operating efficiency for pipeline systems in such conditions. It can be noted also that increase of number of the researches devoted to rise of operating reliability of pipelines and determination of the efficient indicators of transportation of natural gas and its mixtures with other gases are observed during recent years [6–8].

Use of internal smooth coatings is one of the known ways for operating efficiency rise of main gas pipelines. At present time, efficiency of use of internal smooth coatings for main steel gas pipelines is confirmed, and epoxy internal smooth coatings are widely applied in such pipelines [9]. The value of roughness of a pipeline internal wall surface is one of the main factors having influence on energy losses during natural gas transportation through steel pipelines. Lowering of roughness and providing smoothness for different surfaces is actual for many industries such as machine-building [10], mining [11], oil and gas complex [12]. Internal internal smooth coatings allow to decrease roughness of internal wall surface of pipelines [13]. Additionally, internal internal smooth coatings provide solving the problem of protection of internal wall surface of pipelines from corrosion defects. It is rather actual meaning development of hard-to-recover deposits [14], and, based on this factor, the applying coatings should provide protection of internal wall surface of pipelines from corrosion, hydrate formation and embrittlement [15–17].

At present time, epoxy coatings are used as internal smooth coatings for main pipelines, their efficiency for large-diameter pipes was confirmed during operation [18]. These coatings consist of two components: the component A, presenting directly epoxy resin, and the component B, which is a solidifier (often amine-based) [19]. It should be mentioned that these coatings are sensitive to increased embrittlement due to continuous jointing and polymerization during solidification. Gradually these coatings become relatively hard and lose their elasticity. The factor of low temperatures can have additional effect on applied epoxy coatings in the Far North conditions, what accelerates embrittlement process of coatings owing to weakening of intermolecular bonds. Embrittlement of coatings and lose of their elasticity can lead to failure of coating adhesion with steel substrate and its sag from the pipe surface, especially during mounting and laying of a pipeline. This period is characterized by the maximal bending stresses in a pipeline [20].

In connection with the above-mentioned factors, such special conditions require us of the new internal smooth coatings which will have high antifriction, physical and mechanical and protective properties. The coatings on the base of fluorine-containing polymers having protective [21], hydrophobic [22], antifriction [23] properties as well as high cold resistance [24] can be listed as prospective variants. Additionally, it is mentioned in several sources that fluoroplastic pipes are characterized by the minimal value of absolute roughness [25].

Low adhesion strength of fluoroplastic coatings in relation to a coated steel surface is their main disadvantage. In order to rise adhesion bonding between a fluoroplastic coating and steel substrate, preliminary laser processing [26] as well as application of adhesion layers (e.g. via phosphatizing, which provide additional surface protection from corrosion damages [27]) can be used. The authors of this article have developed the method for rise of adhesion strength of fluoroplastic coatings on substrates of carbon and low-alloy steels, including simultaneous operations of preliminary laser processing and cold phosphatizing [28, 29]. This processing allows to rise significantly adhesion of fluoroplastic coatings to steel surface due to forming uniform surface relief after laser processing and forming of micro-crystalline phosphate film after cold phosphatizing. These operations create the developed uniform surface relief, which is able to adsorb a coating and to provide its total quality of bonding with a surface. On the contrary, sandblast processing, which is used at present time [30], is characterized by chaotic features of created relief with large amount of local ledges and cavities, so-called "pockets", what provides the conditions for appearance of discontinuity flaws during coating application.

The problems of damage of a internal smooth coating in the area of welded seam during mounting of a gas pipeline also remain actual. In order to save a internal smooth coating during welding works, the special technical solution was developed. It includes electric arc deposition of aluminium or its alloys in the area 100–150 mm from pipe edge, what allows to obtain relatively smooth welding seam with increased corrosion resistance [31]. In this case it is possible to apply coating along the boundary of processing area of pipe edges, what leads to small decrease of a flow capacity by 0.08 % [32].

The aim of this work is examination of possibility of use a fluoroplastic coating for gas pipelines as a new and prospective coating, which was not used before. The research includes comparative analysis of physical and mechanical properties of epoxy coatings and fluoroplastic coatings during providing special surface preparation for fluoroplastic coating. This analysis was realized via preliminary laser processing and consequent cold phosphatizing, directed on obtaining strong adhesion bond between fluoroplastic coating and steel surface.

Materials and methods

Pilot samples for impact strength testing and elasticity testing (by Ericsson) present steel plates with size 150 × 70 × 1 mm from steel 08kp. Before coating application, these plates were processed depending on coating kind. The scheme of plates processing for each coating is presented below.

Preliminary sandblast processing was carried out for plates with epoxy coating applied. This kind of processing was chosen as the most widely distributed one before application of polymer coatings on steel pipelines [30].

Preliminary processing, including laser treatment and cold phosphatizing was conducted for those plates, which were applied by fluoroplastic coating, in order to improve surface adhesion parameters [28, 29].

Then, dual-component epoxy coating , which is used at present time as a internal smooth coating for main pipelines, was applied on the plates with previous sandblast processing. This coating consists of the component A (epoxy resin) and the component B (amine solidifier). The component A was thoroughly mixed previously, then these components were mixed in mass proportion A/B 5.4:1 ± 5 %. Then the obtained mixture was applied on the prepared plate with consequent drying during 15 min in the air and 30 min in the drying box at the temperature 150 °C for acceleration of jointing and polymerization processes.

Fluoroplastic enamel FP-566 was applied on the plates with preliminary laser processing and consequent cold phosphatizing. According to the technical requirements of a producer, drying time makes 3 hours.

2 series of the samples were prepared for impact strength testing at various temperatures:

– the samples for coating impact strength testing at normal temperature 20 ± 2 °C;

– the samples for coating impact strength testing at the temperature −25 ± 2 °C, which is stipulated by the average negative temperature in the Far North regions.

The plates for testing of the samples for coating impact strength during extension (elasticity by Ericsson) were prepared in the similar way.

To provide testing for bending strength, the plates of black sheet with size 20×100×0.25 mm were fabricated. Then these plates were rubbed with emery and processed by technical alcohol for removal of residual contaminations. Application of epoxy and fluoroplastic coatings on these plates was realized according to the previously described scheme.

To examine surface roughness after application of the examined coatings, the plates manufactured according to the technique for studying impact strength and elasticity by Ericsson were used. Two samples for each of these coatings were prepared.

Thickness of obtained coatings was measured by the thickness meter ET600 for paint coatings.

Measuring of impact strength was carried out by the sensor "Konstanta-U1" according to the GOST R 53007-2008 [33]. A hammer pin with mass 1 kg and diameter 8 mm was used. Before testing at negative temperature, the prepared samples were preliminarily cooled to the preset temperature in a heat-and-cool chamber VLK-08-500 during at least 2 hours. Damages after strike by a hammer pin were determined visually and using an enlarging lens.

Measuring of the coating impact strength during extension (elasticity by Ericsson) was conducted by the sensor "Konstanta-ShE", also known as an Ericsson press sensor. Testing was carried out according to the GOST 29309-92 [34]. The control of coating destruction was executed visually and using an enlarging lens.

Maximal bending value, which can be withstood by a coating until its deformation and destruction, was evaluated visually using the sensor "PROMT IZGIB" according to the GOST 31974-2012 [35].

Microstructure of the samples after coating destruction was examined by the microscope Leica DMIL HC.

Surface roughness was measured on the prepared samples using HOMMEL TESTER T1000 profilometer. Obtained roughness values were recalculated to the equivalent values for polymeric pipelines or pipelines coated by polymeric lining via the formula (1) [36]:

$$K_e = 2 \cdot Ra^{1.33}, \quad (1)$$

where Ra – arithmetical mean deviation of the profile, μm.

Results and discussion

The research on determination of the coating impact strength examined two series of samples at various temperatures. Two samples for each of the examined coatings were prepared for testing at each temperature. Coating thickness was measured at each sample before testing. The average coating thickness was 90–110 μm, what corresponded to the standard one [37].

The height of a hammer pin dropping was determined for epoxy coating (EC) and fluoroplastic coating (FPC), it was equal to 50 cm; at this height coating is destructed. The results of these researches are presented in the **Fig. 1**.

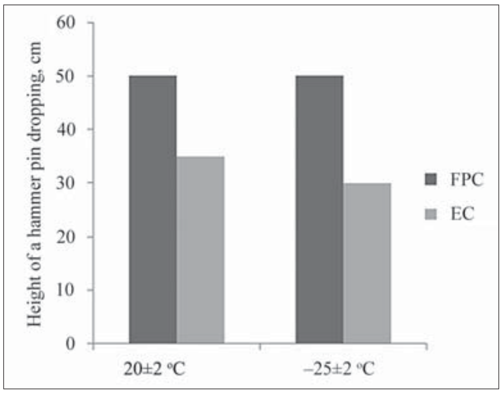


Fig. 1. The results of the coating impact strength measurement

When studying the deformed parts of plates after strike, it was revealed that fluoroplastic coating was not subjected to destruction at the normal and negative temperatures after 5 parallel measurements in different parts of the examined plates.

At the same time destruction of epoxy coating was occurred at the normal temperature (at the height of a hammer pin dropping 35 cm) and at the negative temperature (at the height of a hammer pin dropping 30 cm). Decrease of the height of a hammer pin dropping before coating destruction can be evidently connected with coating embrittlement caused by braking of the process of stress relaxation. The pictures of epoxy coating destruction at the normal temperature are displayed in the **Fig. 2**. The obtained damages are identified as cracks; their further development can lead to adhesion loss and coating separation from steel substrate.

It can be concluded that fluoroplastic coating has more resistance to short-term impact loads in comparison with epoxy coating. High resistance of fluoroplastic coating can be connected small value and rate of stresses elevation in macromolecular chains, which are caused by composition of polymeric coating. Additionally, this kind of testing confirmed high adhesion of fluoroplastic coating to steel substrate, which was processed by the method developed by the authors [28, 29].

High resistance of fluoroplastic coating can improve operating reliability of pipelines. For example, impact effects on a pipe can be inevitable during transportation and laying of pipelines, what can lead to cracking and separation of epoxy coatings during pipeline operation. In its turn, it can lead to decrease of repair interval and additional expenses.

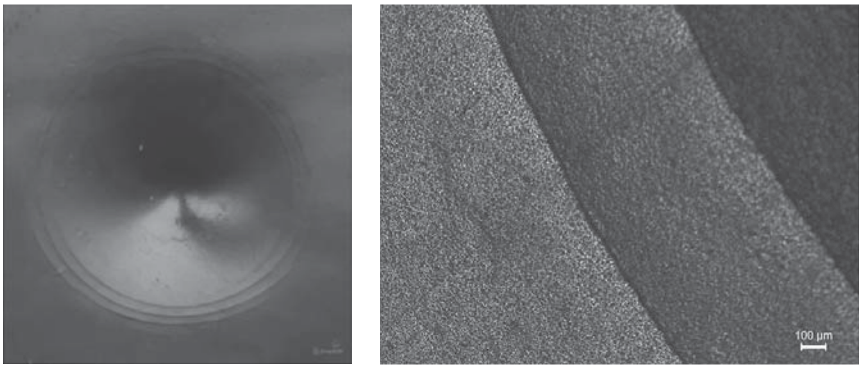
The research on determination of the coating strength during extension (elasticity by Ericsson) considered 2 samples for each of the examined coatings, with 3 parallel measurements for each sample.

The following results were obtained after testing:

– destruction of the samples with epoxy coating occurred at the depth of pin indentation 5.5 mm (average value);

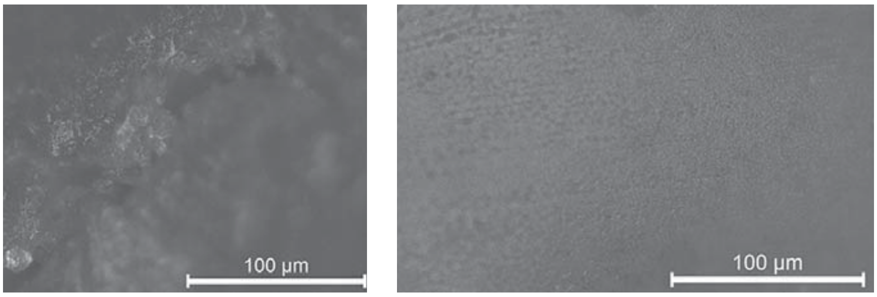
– destruction of the samples with fluoroplastic coating didn't happen at the depth of pin indentation 8.5 mm.

Micro-picture of the sample after testing is presented in the **Fig. 3**. It can be seen that epoxy coating destructed at smaller value of pin indentation. Lower elasticity of epoxy



a *b*

Fig. 2. Damage of the epoxy coating after strike, micro-picture (*a*), magnification x10 (*b*)



a *b*

Fig. 3. Coating after testing for extension: micro-picture of epoxy coating, magnification x20 (*a*), micro-picture of fluoroplastic coating, magnification x20 (*b*)

coating can be evidently explained by polymer composition and internal building, which stipulate larger sensitivity to accumulation of internal stresses and origination of the areas with essential overstresses, leading to cracking.

Testing for bending strength was carried out for evaluation of the maximal bending value, which can be obtained by a coating until deformation and destruction, as well as for additional evaluation of elasticity of considered coatings.

To conduct the testing, 3 plates of black sheet, coated by the examined coatings, were prepared for each of rod diameters. **Fig. 4** displays the testing sensor.

Fig. 4. The sensor for bending strength testing

When testing, the plates were bent around rods from the maximal diameter 20 mm. It was established on the base of the results of conducted testing with 3 control plates, that epoxy coating withstands 5 mm bending, while minimal withstanding bending value for fluoroplastic coatings makes 1 mm. Smaller maximal bending value of epoxy coating can be stipulated by the same causes as its smaller elasticity in comparison with a fluoroplastic coating.

High elasticity of fluoroplastic coatings provides their extension during variation of substrate linear dimensions (presented by pipe surface) as a result of temperature and humidity gradients. Additionally, deformation of a pipeline location can occur as a result of ground swelling or its subsidence, what is actual in the conditions with large temperature amplitudes.

Lower elasticity of epoxy coatings can lead to cracking and separation of a coating under effect of similar factors, especially at low temperatures.

To evaluate roughness of obtained coatings, 5 parallel measurements were carried out on 2 samples in their different sections for each coating kind. When applying the coating via pneumatic deposition on the prepared plates, the measurement results of arithmetic mean deviation of profile for 10 measurements on 2 plates were Ra = 0.420 μm for epoxy coating and Ra = 0.373 μm for fluoroplastic coating. Then the coefficients of equivalent pipe roughness (these pipes were coated by epoxy and fluoroplastic coatings) were determined via the formula (1), their values are equal to $K_{ee} = 0.631$ for epoxy coating and $K_{ef} = 0.539$ for fluoroplastic coating.

Technical literature presents the data that hydraulic roughness limit makes 3–4 μm for large diameter pipes, it is equal to thickness of viscous laminar underlayer for turbulent gas flow [38]. Thus, additional decrease of the mean roughness value provides no effect. So, it can be concluded that epoxy and fluoroplastic coatings have approximately equal potential to provide hydraulic efficiency of a pipeline.

Nevertheless, it should be mentioned that additional factors, such as surface energy of polymers, which is able to provide additional effect on thickness of laminar underlayer, were not examined in this research.

Pressure losses for two kinds of gas (natural gas (NG) with methane content 98 % and more, and natural ethane-containing gas (NEG)) were evaluated according to the technique presented in [39]. It is shown that NEG transportation part increases. Pressure dropping along pipeline length, with established section length 100 km, is presented in the **Fig. 5**, depending on its daily productivity when using internal smooth coating or without it. The coefficient of equivalent roughness was considered as $K_e = 0.01$ [39] for pipes without coating and $K_{eg} = 0.003$ for pipes with internal smooth coating (equal to the thickness of viscous laminar underlayer).

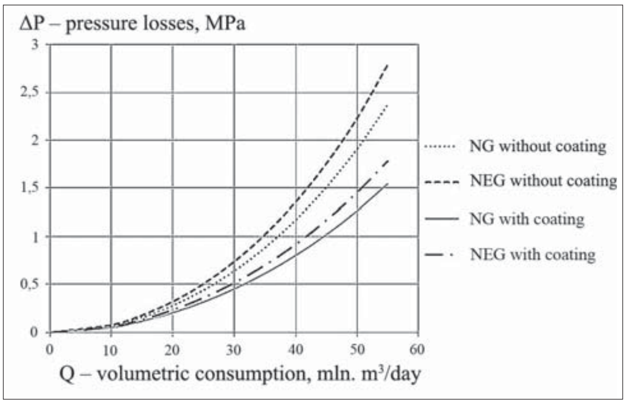


Fig. 5. Pressure dropping for selected pipeline length

It can be seen from the Fig. 5 that pressure losses along the pipeline length decrease approximately by 1.5 times in the case of using internal internal smooth coating. It is especially actual for transportation of gas with increased content of ethane and other components of the hydrocarbon row. It can be concluded that accumulating effect of pressure losses during transportation of ethane-containing gas without using internal internal smooth coating leads to rise of expenses for pressure holding in a main pipeline, as well as to lowering of energy efficiency.

Conclusion

1. Physical and mechanical parameters of epoxy and fluoroplastic coatings were analyzed as a result of this research. This analysis allows to testify synonymously that fluoroplastic coatings are characterized by higher mechanical properties in comparison with epoxy coatings.

2. Testing of coatings for impact strength at normal and negative temperatures displays high strength of fluoroplastic coating in comparison with epoxy coatings. Higher value of this indicator allows to provide more reliable mounting and operation of a pipeline. Testing of coatings for strength after extension and bending strength also displayed that fluoroplastic coating is more elastic. Lower elasticity and high brittleness of epoxy coatings can lead to adhesion failure and coating separation during variation of pipeline linear dimensions or its location as a result of the effect of the complex of physical and climatic factors.

3. It was established on the base of evaluation of the coefficient of equivalent roughness that the coatings have approximately equal potential for providing hydraulic efficiency of a pipeline, which is restricted by thickness of viscous laminar flow underlayer. Use of internal smooth coatings during transportation of natural gas with increased content of ethane and more heavy components allows to decrease pressure losses along the pipeline length by 1.5 times.

4. Based on the obtained results of comparative analysis of physical and mechanical parameters of epoxy and fluoroplastic coatings, and taking into account use of special surface preparation in the form of laser processing and cold phosphatizing (which provides string adhesion bond between fluoroplastic coating and steel surface), it can be recommended to replace epoxy coatings on fluoroplastic ones for main pipelines located in the Far North regions.

Autoclave studies of fluoroplastic coatings applied on steel surface of a pipeline on resistance to variation of gas and hydrodynamic pressure can be considered as prospective directions of future research. CIS

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