Investigation of structure and properties of welded joints of pipe steels

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Abstract. The work is devoted to the study of microstructure and crack resistance of welded joints of pipe materials of main gas and oil pipelines for the Far North regions. Reliable operation of pipelines in harsh climatic conditions of such regions can be provided by the use of materials that have a combination of high values of strength, toughness, cold resistance and weld ability. The results of studies of samples from large diameter pipes with an operating pressure of up to 7.4 MPa at test temperatures of -10 and -20 °C. are presented. These pipes are made of hot-rolled low-carbon low-alloy steel. Various welding methods were used to produce welded joints: high-frequency induction welding, multi-arc automatic welding, laser and hybrid welding. This allowed us to evaluate the influence of the heating and cooling rate during welding on the characteristics of the structural States of the weld, the fusion line, and the overheating area in the zone of thermal influence. It was revealed that a rough needle structure of Vidmanshtett is formed in the zone of overheating of the longitudinal seam at a high cooling rate. Using a low cooling rate allows you to get the Vidmanshtett structure within 2-3 points. It is shown that the crack resistance of the base metal of the pipes practically does not change with a decrease in the test temperature. The values of crack resistance for the metal of the zone of thermal influence have a large spread, which may be due to the influence of technological features of cooling the pipe billet after welding.

1. Introduction
The development of pipeline transport in Russia is associated with the construction of large Russian, Intercontinental and transnational pipeline systems. In the course of improving the methods of construction of gas and oil pipelines, higher requirements for materials for the manufacture of pipes are put forward [1, 2].

The increase in diameters and pressure, pipe wall thicknesses, improvement of welding technologies cause tightening not only in the requirements for mechanical parameters, chemical composition of steels, but also to the production technology of sheet metal, pipe forming processes, as well as physical means of product quality control.

The microstructure in the heat affected zone (HAZ) of welded joints of pipe steels of the line of fusion of the weld with the base metal varies continuously and is determined by the cooling rate, chemical
composition and hardenability of steel, grain size and degree of homogenization of austenite by carbon content, alloying elements and microeconomic before transformation [3, 4]. The main structural changes occur in the following zones of HAZ:
- large grain area directly adjacent to the confluence line;
- areas of complete and partial recrystallization;
- heated area near AC1.

2. Materials and methods
The objects of research were materials of various zones of welded pipe joints, which can be used in the installation of designed oil pipelines. For the study, samples of pipe material were obtained, the chemical composition of which is presented in table 1.

| Pattern number | C  | Mn  | Si  | \(\Sigma(V+Nb+Ti)\) | N  |
|----------------|----|-----|-----|----------------------|----|
| 1              | 0.12 | 1.32 | 0.22 | 0.12               | ≤0.02 |
| 2              | 0.11 | 1.44 | 0.40 | 0.08               | ≤0.02 |
| 3              | 0.13 | 1.55 | 0.24 | 0.15               | ≤0.02 |
| 4              | 0.09 | 1.66 | 0.39 | 0.08               | ≤0.02 |
| 5              | 0.11 | 1.47 | 0.28 | 0.13               | ≤0.02 |
| 6              | 0.12 | 1.33 | 0.23 | 0.12               | ≤0.02 |
| 7              | 0.12 | 1.46 | 0.41 | 0.09               | ≤0.02 |
| 8              | 0.08 | 1.68 | 0.37 | 0.07               | ≤0.02 |
| 9              | 0.10 | 1.65 | 0.44 | 0.08               | ≤0.02 |
| 10             | 0.12 | 1.45 | 0.23 | 0.13               | ≤0.02 |

The average values of the chemical composition of the base metal of pipes are given in accordance with table 5 clause. 9.2.2. GOST R ISO 3183-2009-section "Welded pipes" L-L450M or X65M (no more)

Steel grade of control sample 12Mn2VNb (12Mn2V)

In accordance with GOST R ISO 3183-2009, the grade of material is defined as steel 12Mn2VNb.

Studies of the microstructure of the zones of welded joints were carried out using an optical metallographic microscope. The analysis of the microstructure of the base metal and weld metal of all pipes was carried out in the non-etched and etched states. The plates were manufactured in accordance with the requirements of GOST 5639 and GOST 5640.

Crack resistance tests were performed using INSTRON 8801 test equipment. Characteristics of crack resistance \(\delta c\) were determined by the results of tests of standard samples. Test samples made with incisions in the base metal zones (BM) and heat-affected zones (HAZ) were cut from the templates in such a way that the longitudinal axes of the samples were directed in the circumferential directions of the pipes, since their welds had longitudinal directions with respect to the pipes.

3. Results and discussion
The speed of heating and cooling during welding depends on several factors: the thickness of the metal,
the welding current while maintaining the welding speed, the temperature of the metal billet, the number of passes during welding, heat input welding. Each of the above factors and their totality can significantly affect the characteristics of the structural States in each of the four selected zones in steel of different alloying.

The structure of low-alloy pipe steel is not resistant to high-temperature welding effects, so during welding in the zone of thermal influence of the weld, a number of structures with different physical and mechanical properties are formed.

During cooling after welding as a result of $\gamma \rightarrow \alpha$ transformation in low-carbon low-alloy tube steel, the structure change begins with the release of free ferrite, and an unfavorable structure of coarse-grained needle ferrite with low impact values is formed at the fusion boundary.

The most unfavorable zones in the welding of ferrite-perlite pipe steels are the fusion boundary and the zone of softening at the site of full recrystallization of the HAZ due to the formation of a significant proportion of large polygonal ferrite due to the decrease in the cooling rate associated with a high level of heat investment in high-performance multi-arc welding.

In areas of partial recrystallization (since the structure of the base metal contains in addition to ferrite and cementite), when heated in the region of $\alpha + \gamma$, the origin of austenite occurs first in the form of separate areas mainly along the grain boundaries, and then their growth. Upon subsequent cooling, the resulting austenite is completely or partially converted into a ferrite-carbide (ferrite-perlite) mixture. The areas of complete and partial recrystallization formed at a lower temperature compared to the HAZ areas located closer to the fusion boundary have the highest viscosity.

In this regard, in order to obtain satisfactory viscous properties of the pipe metal, especially in the area of negative temperatures, it is necessary to limit the linear welding energy. This limitation is caused to the fact that with increasing linear energy, the total length of HAZ increases, and the sizes of the newly formed phases and structural components increase in the process of recrystallization.

The study of the metal longitudinal welded joints of pipes for oil pipelines, aimed at assessing the microstructure and its impact on the complex properties of the material. The microstructures presented in the figure are typical Widmanstett structures with different degrees of severity and sizes of needle ferrite, which primarily depends on the cooling rate of the zone of thermal influence of the weld. It is known that as the cooling rate increases (with a constant carbon content in steels), the shape of ferrite grains gradually changes from polygonal to needle-like.

As indicated in [5], when cooled in the heat-affected zones of both steels (in the areas of overheating adjacent to the fusion boundary) ferrite needles grow from the borders to the center of the austenite grains and they have a distinct orientation: the plane of the dodecahedron ferrite plates (110) and located parallel to octahedron planes of the austenitic grain (111) and close-packed direction (111) body-centered cubic structure of ferrite parallel close-packed directions the (110) face-centered cubic lattice of austenite. This mutual arrangement of the two phases provides the best coupling between the two structures and the lowest surface energy. The figure shows typical structures of needle ferrite formed by the above mechanism – with a clear orientation of the needles in the specified crystallographic directions, the space between the needles is filled with ferrite-cementite aggregates of pearlite origin.

During the analysis of microstructures the probability of preservation of some quantity of residual austenite in Widmanstetter structures of lines of fusion of steels as it is known that in case of partial formation of bainite in mezhigolehatom space in structures of steels the residual austenite has to remain was investigated. However, the studies did not reveal traces of bainite and residual austenite in the structures of both steels.

The high cooling rate of the weld in the steel pipe No. 1 leads to the formation of a rough needle structure (see Figure 1, a), on average 4-5 points on a scale of 4 series A according to GOST 5640; while in steel pipe No. 2, due to more favorable conditions for the formation of a weld, the beam of the
Widmanstett structure (see Figure 1, b) is within 2-3 points on a scale of 4 according to GOST 5640. Based on the studies of the microstructure of the zones adjacent to the border of fusion welds in steels (lines of fusion), we can conclude that the value of fracture toughness of fusion line of the two steels is directly dependent on technological parameters of welding, increasing the heat input the welding causes the growth of austenite grains in the line of fusion of the weld and during accelerated cooling to the formation of ferritic structures dominating in the group with increased fragility, especially in the area of negative temperatures.

Figure 1. Weld, fusion line and overheating area in the heat affected zone weld: a-pipe 1; b-pipe 2

The numerical values of fracture toughness of steels is a function of the size and shape of needles of ferrite grain in steel pipe № 2 with the best combination of fracture toughness – Widmannstetter structure of the line of fusion level 2-3 on a scale of 4, A GOST 5640; in the case of steel pipe № 1 with the worst indicators of fracture toughness – as a 4-5 score structure Widmannstetter.

In work tests on crack resistance of the pipes welded with different speed of movement of a welding source on technology of high-frequency induction welding in a zone of the basic metal and a zone of overheating of welded connection were carried out. The parameter δc (CTODmin) was used as a crack resistance parameter - critical opening of the crack banks in the dead-end part during its straining. A total of 5 clippings (templets) from two pipes were tested (see table).

Table 2. The results of the tests fracture toughness CTOD min, mm metal pipes and overheating zones of welded joints

| № of sample | Temperature, °C / place of incision | Base metal | | | Overheating zone | |
|-------------|-----------------------------------|------------|------------|---|---|
|              |                                   | -10        | -20        | -10 | -20 |
| 1-1          |                                   | 0.62       | 0.68       | 0.07 | 0.28 |
| 1-2          |                                   | 0.72       | 0.69       | 0.11 | 0.10 |
| 1-3          |                                   | 0.77       | 0.78       | 0.09 | 0.14 |
| 1-4          |                                   | 0.76       | 0.99       | 0.12 | 0.14 |
| 1-5          |                                   | 0.61       | 0.61       | 0.12 | 0.15 |
| 2-1          |                                   | 0.68       | 0.76       | 0.51 | 0.47 |
| 2-2          |                                   | 0.79       | 0.75       | 0.44 | 0.38 |
| 2-3          |                                   | 0.79       | 1.01       | 0.37 | 0.35 |
| 2-4          |                                   | 0.67       | 0.66       | 0.36 | 0.37 |
| 2-5          |                                   | 0.60       | 0.59       | 0.33 | 0.41 |
The results of the studies allowed us to establish that the values of crack resistance of the main material of the pipes are close in values. For the metal of the superheat zone there is a significant spread of data, which may be the result of the peculiarities of the formation of the microstructure in the zone of thermal influence due to different modes of welding processes.

4. Conclusion
The paper analyzes the influence of the metal microstructure of the longitudinal weld seam of the main gas and oil pipelines. The most common welding technology used for oil and gas pipes is the so-called "high frequency induction technology", which is the application of induction current on the outer surface of the pipe, able to create a strong weld and tightly connect the two sides of the steel billet. Multi-arc automatic welding, laser and hybrid welding are also used. By adjusting the speed of the welding source, it is possible to achieve the formation of various microstructures in the weld zone. It was established that:

1. the high cooling rate of the longitudinal seam (pipe № 1) leads to the formation in the overheating zone of the coarse needle structure Widmannstetter, estimated 4-5 points GOST 5640; while in steel pipes with low cooling rate (pipe № 2) due to more favorable conditions for the formation of the weld structure Widmannstetter score is within 2-3 points GOST 5640;
2. the fracture toughness of the base metal of both pipes are almost identical, and the difference in the magnitude of fracture toughness of metal in the zone of overheating of welded joints of pipes can only be explained by differences in the technological characteristics of the cooling tubular workpieces after welding and is connected with the peculiarities of the formation of the microstructure of the heat affected zone of a welded joint.

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