Welding and Assembly Operations in the Course of Main Pipeline Construction in a Low Temperature Environment

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Abstract: - The article deals with the current welding issues of pipeline construction in the Far North of Russia in order to provide solutions to ensure their operational reliability and environmental safety, as well as to reduce any risks associated with the destruction of welded joints. Based on the analysis of the results of experimental studies of the pipe joint welding thermal cycles, metal-physical studies, and calculation methods, the article provides the materials on the development of additional requirements for welding technology at low temperatures in the Far North, when metals lose their viscosity and plastic properties and become prone to hot and cold cracking. It was found that the choice of the optimal weld thermal cycle allows achieving high mechanical performance of metal near any welded joints and also provides for the high metallurgical quality of the weld metal. The presented results of scientific research aimed at the reliability improvement of the welded joints of the PJSC Transneft's pipeline system at low temperatures in the Far North were used in the development of regulatory documentation for welding technology.

Key-Words: - welding, welded joint, crack resistance, low temperatures, heat-affected zone, weld thermal cycle, strain capacity, cold cracks.

1 Introduction

Over the past two decades, the company PJSC Transneft has been building a number of pipelines in the Far North, in particular: Eastern Siberia – Pacific, Arctic – NPC Purpe. The total length of those pipelines will be over 3000 km. The ambient temperature in the welding and installation area is far below –20°C, down to –40°C [1-4]. In the construction of the pipelines, K56–K60 strength grade pipes with a diameter of 1020-1220 mm and wall thickness of 11-27 mm are mainly used.

At present, works at negative temperatures are performed with the general approach to the welding technology, which assumes that the preheating of edges to specified temperatures in the range of 100-150°C is sufficient to provide the required temperature conditions for welding. However, experience in the construction and repair of main pipelines has shown that the welding technology at low ambient temperature should differ from the existing one. This includes the requirements for welding materials equipment, as well as for the temperature conditions of the technological operations and procedures. Therefore, it was deemed necessary to develop new documents to set standards and requirements for welding operations in the Far North.

1.1. Problem

Domestic and foreign experience in the construction and repair of pipelines in the Far North shows that at low temperatures (below 0°C), the course of metallurgical processes during welding has a number of specific peculiar features, both in the process of the weld pool crystallization and in the selection of welding conditions, which determines the mechanical properties of the weld joint as a whole. Therefore, in order to achieve a high-quality weld joint, it is important to choose the appropriate weld thermal cycle, which would determine the optimal structure of the welded joint areas [1, 2].

At low temperatures, the performance of welded joints of pipe steels deteriorates: their hardness and the ultimate tensile strength increase; while plasticity and impact strength decrease (Fig. 1). The main performance indicator for weld joints is the critical brittle point, i.e. the temperature at which a sharp decrease in the impact strength occurs. The lower this temperature, the more reliably the welded joint performs.

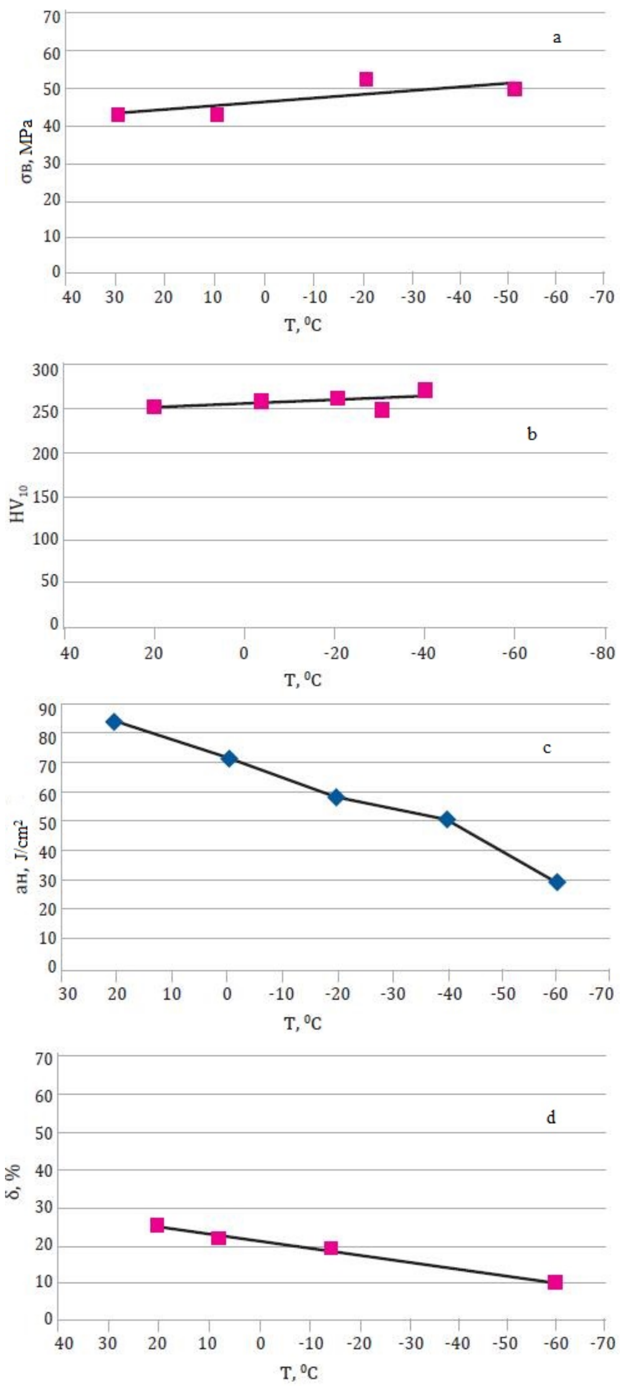

Fig. 1. The effect of temperature on the mechanical properties of weld metal.

When the metal of the weld pool and the parent metal crystallize in the heat-affected zone (HAZ) at low temperature, the cooling rate increases. As a result, gases and oxides are prevented from escaping from the molten metal, which increases the content of hydrogen, oxygen, nitrogen, and nonmetallic inclusions in the weld metal and can lead to the formation of pores and hot cracks.

In the course of welding at low temperatures, the possibility of hot cracking in the welds is further aggravated with an increase in the rate of elastic-plastic distortion in the critical temperature range, where the heated metal is already brittle. The probability of cold cracking in the HAZ is especially high in pipe joints with the pipe wall thickness of 16 mm or more.

In winter, the welding and technological properties of electrodes deteriorate, mainly due to moisture ingress, which leads to additional porosity in the weld metal. The increased heat removal during welding of thick-walled pipes reduces the base metal penetration, which results in faulty fusion [1, 4-8].

As the temperature of the ambient air decreases, the plasticity of the weld metal and its resistance to crystallization cracks decreases, the equipment performance deteriorates, which increases the probability of formation of weld defects, and the probability of brittle fracture of the joint during its welding or repair increases [2, 8].

The implementation of welding technology at low temperatures requires additional measures, both in terms of the technological process itself (selection of appropriate heating and welding conditions) and in terms of maintaining the equipment and physiological state of the personnel [1, 2, 4, 5, 9-12].

1.2. Additional requirements for welding technology and materials

The additional requirements include the following:

– The used pipes should be made of metal intended for structures operating at low temperatures.

– The welding equipment must be specially adapted for operation at low temperatures.

– The welding materials should provide for the impact strength of the weld metal of at least 50 J/cm2.

– The weld edges should have the double-groove design. In this case, welding should be preferably performed simultaneously from both sides.

– The weld joints should have no welding defects that would contribute to the brittle rupture of the structure.

– When designing junction structures, one should avoid sudden changes in the cross-section of the coupled elements and, if possible, avoid coupling elements of different thickness.

– When assembling pipe joints, it is preferable to use assembly-welding rigs instead of rigid tack welds, to avoid causing unnecessary strain in the welded joints.

– A special approach to the selection of the weld thermal cycle (WTC) conditions is required. WTC should ensure the degassing of molten metal and removal of any nonmetallic and slag inclusions.

– All joints should be welded without interruption. The welding should not be ceased before achieving the design size of the weld and no sections should be left unfinished. It is necessary to provide retarded cooling of welded joints with heat-shielding bands at a distance of at least 300 mm from the weld joint in each direction.

– Preliminary and concurrent heating of the main metal is required. When welding multiple-layer joints, all layers of the joint should be heated.

– The weld root and subsequent layers should be deslagged by grinding only after heating the joint to a temperature of 100-120°C. It is inexpedient to remove metal with a chisel because of the possibility of brittle fracture of the metal.

– The defective parts of the seam should be welded only with preliminary and concurrent heating. When welding defective sections, lime fluorspar electrodes should be used.

– The welding operator and the welding area should be protected from wind and precipitation; special heated enclosures should be equipped. The workplace should be equipped with a hand-warming device. It is desirable to use electrically-heated clothes at an air temperature below –40°C and supply fresh air for the welding operator to breathe.

1.3. The object and line of research

Technologically, the main problem in pipeline welding at low temperatures is to ensure the reliability of the welded joints. The most effective way to solve this problem is to develop additional processes to compensate for the effects of low temperatures. The specialists of NII Transneft LLC researched and analyzed the influence of the weld thermal cycle conditions on the nature of the course of metallurgical processes in a welded joint during its crystallization and, accordingly, on the mechanical properties of the metal in the high temperature zone during welding.

The research objects were annular welded joints of pipes made of K56 strength grade steels, welded by two processes:

– Manual upward arc welding with basic-coated electrodes (MA welding).

– Automatic welding with flux cored wire in active gases and mixtures (AFCWG welding) with the mechanical welding of the root weld layer with solid wire in carbon dioxide (MSW welding) using the STT technology.

2 Research methodology

The following sequential algorithm was implemented during the research:

– We analyzed the regulatory requirements for the mechanical properties of welded joints (ultimate tensile strength, yield stress, relative elongation, impact strength, hardness level in welded joint areas).

– Based on the requirements for mechanical properties, we determined the requirements for the optimal structure of welded joints by the method of calculation and experiments. The temperature range of austenite decomposition was calculated using a C-shaped decomposition curve. Various structures were experimentally obtained for a wide range of cooling rates in the temperature range of the decomposition from 0.1 to 300°C/sec) (Fig. 2).

– For the three versions of pipe steels, the refined diagrams of the anisotropic decomposition of austenite (ADA) (Fig. 3) were drawn and used to define the actual martensite content as a function of the cooling rate. To use them, we designed a real weld thermal cycle for single-pass (Fig. 4) and multi-pass welding of K56 strength grade pipe steels (Figure 5).

– We analyzed the structural transformations in welded seams for K56 strength grade steels with a content of CE from 0.29 to 0.43. Thus, we found the permissible content of martensite in the heat-affected zone, depending on the carbon content in the steel and the maximum permissible hardness (Fig. 6).

– We developed the physical and mathematical model of the thermal processes during welding for calculation of optimal weld thermal cycles.

– We determined the main criteria for the development of a ranking system for compensatory technological measures. The compensatory measures were systematized and ranked with account of the ambient air temperature, welding method, carbon equivalent, and wall thickness of the welded pipes.

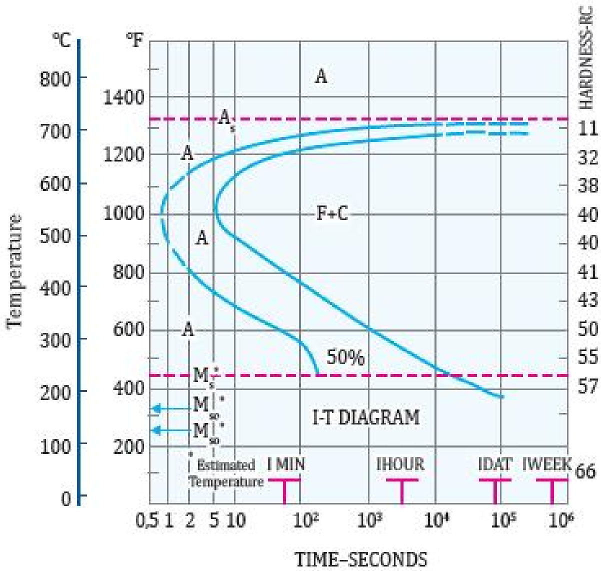

Fig. 2. The isothermal transformation chart for cooling. Steels with C-shaped curves of the beginning and end of austenite decomposition.

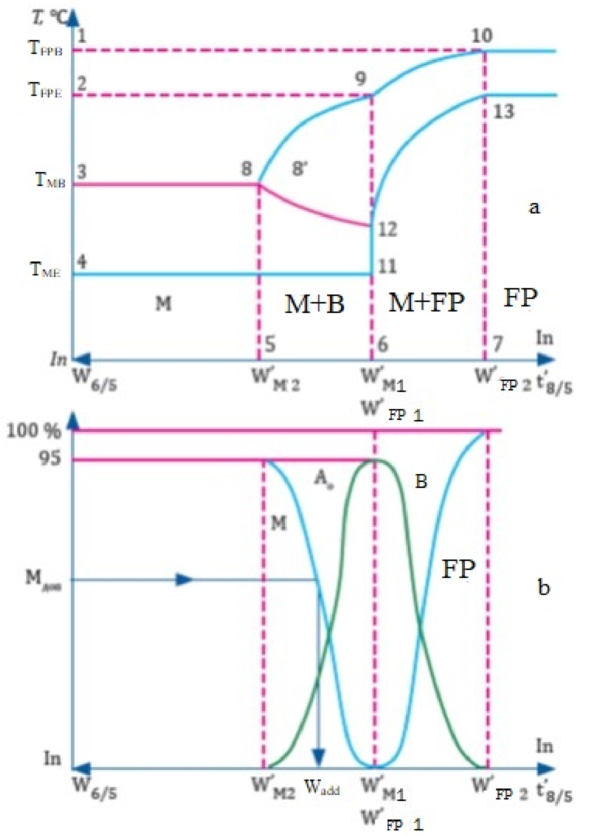

Fig. 3. The typical schematic ADA chart for low-carbon low-alloy steels: T_{FPB}, T_{FPE}, T_{MB}, and T_{ME} are the temperatures of the beginning and end of ferrite-pearlite (FP) and martensitic (M) transformations; W_{FP1}, W_{FP2}, W_{M1}, and W_2 are the critical cooling rates ($W_{6/5}$), at which 1% and 100% of FP and 1% and 95% of M are formed.

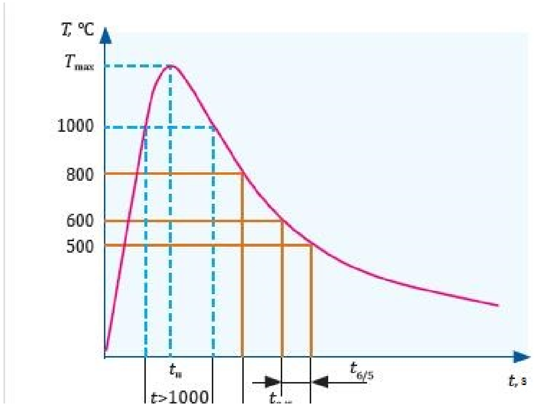

Fig. 4. The weld thermal cycle in the heat-affected zone in single-pass welding and its main parameters: T_{max} is the maximum heating temperature; t_h is the time to reach the maximum heating temperature; t > 1000 is the time of exposure to T > 1000°C; $t_{8/5}$ is the time of cooling from 800 to 500°C; $t_{6/5}$ is the time of cooling from 600 to 500°C.

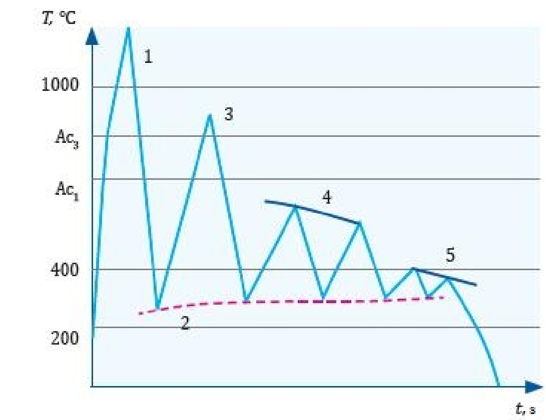

Fig. 5. Weld thermal cycle in the heat-affected zone in multi-pass welding: 1 – quenching cycle; 2 – auto-heating; 3 – the cycle of austenite grain recrystallization and crushing; 4 – temper cycles; 5 – reheat cycles.

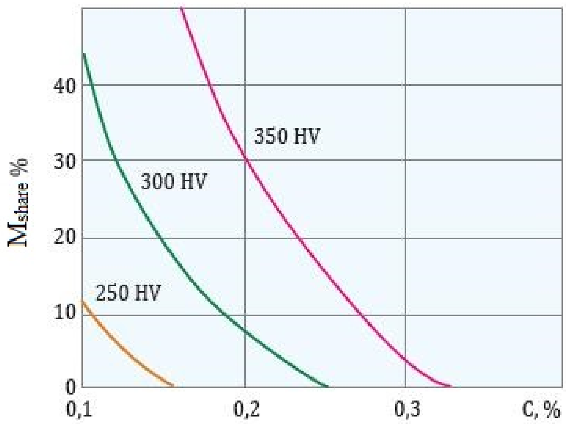

Figure 6. Admissible martensite content in the heat-affected zone, depending on the carbon content in steel and the maximum permissible hardness.

3 Research results

The research established the following:

– The strength, plastic, and viscous properties of the weld metal and weld zone are directly dependent on the metal structure. The optimal structure for the pipe metal and for the weld metal is a fine-grained uniform ferrite-bainite microstructure.

– The influence of the structure on specific indicators of mechanical properties is determined by its morphology. The main parameters determining the morphology of the structure are: the carbon content in the metal; basic alloying and complex microalloying; content of harmful impurities; number of quenching structures; hardness of metal; conditions of the weld thermal cycle.

– An analysis of the structural transformations in welds for K56 strength grade steels of different chemical composition (CE from 0.29 to 0.43) showed that the formation of the martensitic structure in a steel with a higher carbon equivalent begins at lower cooling rates than in a steel with a higher carbon equivalent value. A higher carbon equivalent steel is more prone to hardening (Fig. 6).

– The most efficient process method that influences the structure and, accordingly, the properties of the metal are the adjustment of the running energy by choosing the optimal weld thermal cycle. We determined the parameters that enable developing the optimal weld thermal cycles. We found that the optimal weld thermal cycle should provide a cooling rate in the temperature range of 500-600°C of no more than 40°C/s. We also calculated that with a hardness not exceeding 240 HV10, the probability of hardening structures' formation is significantly reduced.

- The main criterion for the due performance of welded joints operating at low temperatures is the impact strength. With the increase in the strength grade of the pipe metal, the requirements for the higher impact strength indexes are increased.

– The calculation and experimental justification of the required temperatures in the welding process based on the permissible structural transformations in welded joints and the required properties made it possible to obtain an optimal (theoretical) weld thermal cycle that provides for the requirements of structural transformations and properties of welded joints. In the case of a maximum CE content (up to 0.4) in the pipe steel, repeated thermal action in the range of 600-500°C ensures the residual martensite decomposition. With a minimum content of CE (0.29), the absence of martensitic structures is possible already after the first weld pass.

– It has been experimentally confirmed that if the cooling rates are maintained below 40°C/s, a ferrite-bainite structure of the metal is formed, while quenching (martensitic) structures are absent, which ensures the level of impact strength of not less than 62 kJ/cm2.

– The experiment has confirmed that the interlayer temperature (interlayer heating) not only affects the regulated cooling rate, but also ensures proper diffusion of hydrogen, contributing to a reduction in the probability of cold cracking [4, 13-16].

– We determined the criterion for the content of the brittle component in the welded joint: 40% or less. For the established criterion for the content of the brittle component in the welded joint, the critical cooling rates are determined depending on the CE in metal, thickness of metal, welding method, and ambient temperature.

4 Discussion of the study results

1. The research results showed that the implementation of technology of welding at low temperatures between 0 and –50°C for the MA and MSW+AFCWG welding technologies requires additional process operations in terms of adjusting the heat input into the metal.

2. We provided the calculation and experimental justification of the required temperatures in the welding process based on the analysis of the regulatory requirements for the properties of welded joints and structural transformations in welded joints from the viewpoint of ensuring the required properties of the metal.

The analysis of the available data showed that the strength, plastic, and viscous properties of the weld metal, the heat-affected zone, the weld zone are directly dependent on the metal structure. The influence of the structure on specific indicators of mechanical properties is determined by its morphology. The most effective technological method that influences the metal structure and, accordingly, its properties is the adjustment of the running energy by choosing the optimal weld thermal cycle [8-10, 17-22].

It has been experimentally established that providing a cooling rate in the temperature range of 500-600°C not exceeding 40°C/s will make it possible for the weld joint to have such a ferrite-bainite structure that would provide the required values of impact strength.

3. We developed a computational mathematical model of thermal processes for the MA and MSW+ AFCWG welding technologies, which enables calculating numerically the main parameters of the compensation measures for welding at low temperatures.

4. The compensatory measures were systematized and ranked with account of the ambient air temperature, welding method, welded metal thickness, and carbon equivalent. The list of compensation measures for the purpose to achieve the optimal heat input into the metal is provided in Table 1.

Table 1. The effect of low temperatures on the parameters of the weld thermal cycle for various welding methods

<table>
<tr><th rowspan="2">Ambient temperature, °C</th><th rowspan="2">Welding method</th><th rowspan="2">Pipe wall thickness, mm</th><th colspan="3">Compensation measures at CE</th></tr>
<tr><th>0.34 or less</th><th>From 0.35 to 0.41 (inclusive)</th><th>From 0.41 to 0.43 (inclusive)</th></tr>
<tr><td rowspan="2">0 or higher</td><td>MA</td><td rowspan="2">Less than 30</td><td colspan="3" rowspan="2">Preheating to 50°C</td></tr>
<tr><td>MSW+ AFCWG</td></tr>
<tr><td rowspan="2">From 0 to -10</td><td>MA</td><td rowspan="2">Less than 30</td><td colspan="3" rowspan="2">Preheating to 100°C</td></tr>
<tr><td>MSW+ AFCWG</td></tr>
<tr><td rowspan="2">From -10 to -20</td><td>MA</td><td rowspan="2">Less than 30</td><td colspan="3" rowspan="2">Preheating to 150°C and soaking for at least 10 minutes.</td></tr>
<tr><td>MSW+ AFCWG</td></tr>
<tr><td rowspan="2">From -20 to -30</td><td>MA</td><td>Less than 30</td><td colspan="3">Preheating to 150°C and soaking for at least 10 minutes.</td></tr>
<tr><td>MSW+ AFCWG</td><td>Less than 30</td><td colspan="3">Preheating to 150°C and soaking for at least 15 minutes.</td></tr>
<tr><td rowspan="6">From -30 to -40</td><td rowspan="3">MA</td><td>Less than 12</td><td colspan="3">Preheating to 150°C and soaking for 20 minutes + concomitant (interlayer) heating up to 50°C</td></tr>
<tr><td>From 12 to 21</td><td>Preheating to 150°C and soaking for 20 minutes + concomitant (interlayer) heating up to 50°C</td><td colspan="2">Preheating to 150°C and soaking for 25 minutes + concomitant heating up to 150°C</td></tr>
<tr><td>From 21 to 30</td><td colspan="3">Preheating to 150°C and soaking for 25 minutes + concomitant heating up to 150°C</td></tr>
<tr><td rowspan="3">MSW+ AFCWG</td><td>Less than 12</td><td colspan="3">Preheating to 150°C and soaking for 20 minutes + concomitant (interlayer) heating to a temperature of 50°C by a single-flame burner after welding each layer</td></tr>
<tr><td>From 12 to 21</td><td colspan="3" rowspan="2">Preheating to 150°C and soaking for 25 minutes + concomitant heating up to a temperature of 150°C</td></tr>
<tr><td>From 21 to 30</td></tr>
<tr><td rowspan="4">From -40 to -50</td><td rowspan="3">MA</td><td>Less than 12</td><td colspan="2">Preheating to 150°C and soaking for 20 minutes + concomitant (interlayer) heating up to 50°C</td><td>Preheating to 150°C and soaking for 25 minutes + concomitant heating up to 150°C</td></tr>
<tr><td>From 12 to 21</td><td colspan="2">Preheating to 150°C and soaking for 25 minutes + concomitant heating to a temperature of at least 150°C</td><td>*</td></tr>
<tr><td>From 21 to 30</td><td>Preheating to 150°C and soaking for 25 minutes + auxiliary heating 150°C</td><td colspan="2">*</td></tr>
<tr><td>MSW+ AFCWG</td><td>Less than 12</td><td colspan="2">Preheating to 150°C and soaking for 25 minutes + concomitant heating up to 150°C</td><td>*</td></tr>
</table>

Ambient temperature, °C	Welding method	Pipe wall thickness, mm	Compensation measures at CE		
			0.34 or less	From 0.35 to 0.41 (inclusive)	From 0.41 to 0.43 (inclusive)
		From 12 to 21	Preheating to 150°C and soaking for 25 minutes + concomitant heating up to 150°C	*	
		From 21 to 30	Welding is not carried out	*	
Note: * Welding is recommended to be carried out in inventory shelters with controlled ambient temperature					

5 Summary

The research has established that the implementation of welding technologies at low temperatures requires additional process operations related to adjusting the heat input into the metal.

The metallophysical methods have established that the strength, plastic, and viscous properties of the weld metal, heat-affected zone, weld zone are directly dependent on the metal structure. The influence of the structure on specific indicators of mechanical properties is determined by its morphology. The most efficient process method that influences the structure and, accordingly, the properties of the metal is the adjustment of the running energy by choosing the optimal weld thermal cycle.

It has been experimentally established that providing a cooling rate in the temperature range of 500-600°C not exceeding 40°C/s will make it possible for the weld joint to have such a ferrite-bainite structure that would provide the required values of impact strength.

4. Based on the research results, NII Transneft LLC has developed two regulatory documents: “Welding Operations in the Construction of the Main Oil Pipeline and Technological Pipelines at Low Temperatures. Polar Region – NPC Pur-Pe Pipeline System. Production and Quality Control” and "Welding in the Construction of Tanks at Low Temperatures. Polar Region – NPC Pur-Pe Pipeline System. Production and Quality Control.” These regulatory documents regulate welding operations in the Far North at temperatures up to –40°C.

The developed regulatory documentation takes into account the domestic experience in the pipeline construction over the past 30 years, as well as the experience of building similar pipelines abroad and proposes new welding technologies.

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