Investigation of thermal cycles in multi-pass welding of low-alloy steel under subzero ambient temperature conditions

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Ensuring the reliability and durability of welded structures in northern and Arctic regions, where extremely low temperatures significantly affect welding thermal processes, remains a critical issue. Welding under low climatic temperatures increases heat removal from the weld zone, influencing the microstructure and mechanical properties of the joint. Higher cooling rates raise the likelihood of quenched structures forming, which may reduce the fracture resistance of welded joints. This paper presents experimental results on thermal cycles during multi-pass manual arc welding of low-alloy steel 10KhSND at subzero ambient temperatures (–15 °C and –35 °C) and their effect on the hardness of weld zones are also displayed. Temperature fields were recorded using high-precision chromel-alumel and platinum-platinum/rhodium thermocouples. It was found that reducing the ambient temperature to –35 °C increases the cooling rate in the root pass by 49 % compared to room temperature (+20 °C). The study demonstrates that multi-pass welding reduces cooling rates in subsequent layers due to preheating effects. Meanwhile, the heat-affected zone exhibits an 11–12 % decrease in hardness, attributed to microstructural changes induced by thermal cycles. The obtained results hold significant practical value for developing welding guidelines in extreme northern and Arctic conditions, improving microstructure, and enhancing the operational performance of welded joints.

Key words: multi-pass welding, thermal cycle, cooling rate, low-alloy steel, hardness, cooling time, heat input.
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Introduction

Providing reliability and safety of pipeline systems, tank constructions, bridges and other metal constructions in cold climatic regions is an actual scientific and technical problem. At the same time, manufacture of large-size constructions can’t be realized without welding operations at building sites, and volumes of these welding operations can be rather essential. In this case, in the far North and Arctic conditions, where the average annual temperature is below –10 °C and there are more than 200 cold days per year [1], welding operations are often conducted at negative ambient temperatures. Parameters of welding conditions, as well as welding temperature, determine kinetics of welding thermal cycle passing [2]. It is known that structural state and, respectively, mechanical properties of welded joints zones depend on welding thermal cycles [3, 4].

Cooling rate and cooling time are considered as the main parameters of a welding thermal cycle for examination of microstructure in welded joints. In particular, for low- and medium-alloy steels, we are oriented according to the cooling rate within the temperature range of minimal austenite stability 600–500 °C [5]. Cooling time within the temperature range 800–500 °C or cooling rate in the same temperature range is also widely used as a technological indicator [6–8]. It is recognized that the temperature range 800–500 °C of diffusion austenite transformation allows examination of the key technological stages of the cooling process, which determines microstructure, including metal hardness and metal sensitivity to cold cracking etc. [9].

It is known that the thermal welding effect causes unfavourable variations in the structure of a heat-affected zone (HAZ) of an integral connection, which differs essentially by its structure and mechanical properties from the basic metal. Maximal variation of metal structure and properties is observed for the high-temperature HAZ area – an overheating section which has coarse grain structure with low impact strength values and possible forming of quenching structures [10–12]. At the same time, the research [13] showed that steels with low carbon equivalent are characterized by maximal impact strength values. In this case cooling rate was maximal within the examined range, while more alloyed steels have impact strength registered during displacement of cooling time $t_{8/5}$ (within the temperature range 800—500 °C) to the larger values, i.e. optimal cooling rates exist.

In relation with the above-mentioned considerations, it is interesting to watch the influence of lowering climatic temperatures (which are measured during welding operations) on cooling rate and cooling time within the certain ranges of a thermal cycle. It was shown in the experimental researches during 1980-ies [2, 14] that cooling rates of welded joints in welding at low temperatures rise by 25—40 % for the cooling temperature range 600—500 °C, while duration of metal stay within the temperature range 300—100 °C decreases by several times. Depending on a steel grade and welding materials, these circumstances can reduce substantially cold resistance of an integral connection [2]. The conducted review of technical literature on this theme [15] displayed that parameters of thermal welding cycle (in addition to the ambient temperature) depend essentially on sizes of tested samples and weld heat input. At the same time, there is lack of researches relating to the features of thermal cycles during multi-pass welding in the conditions of low climatic temperatures. Thus, it is required to take into account the features of heat distribution for negative environment temperatures during development of the welding technology for metal constructions in these conditions.

The aim of this research is to study the thermal cycle parameters during multi-pass manual arc welding of low-allow sheet steel in the conditions of negative ambient temperatures, and to evaluate its effect on hardness of welded joint zones.

Materials and methods of the research

The welding thermal cycles were examined for low-alloy steel 10KhSND, which is used often for critical metal constructions in the climatic zones with calculated temperature below —50 °C. The examined samples have the following size: the plate 340×350 mm with thickness 14 mm. Based on the technical literature data [15], the selected sizes of samples should allow fixing of cooling rates difference during welding in the conditions of negative ambient temperatures in comparison with the data at the room temperature (+20 °C). Thermal welding cycles didn't vary essentially at different temperatures for small-size plates (with size 200×250×10 mm), due to more intensive heat reflection from sample edges. Increase of the cooling rate for the section of welded joint overheat in comparison with welding at the room temperature was observed for more massive samples (with size 450×250×10 mm). The sheets of the examined steel with thickness 14 mm are used for fabrication of bridge covering. Welding of samples was carried out by electrodes of UONI 13/Moroz kind, which have close strength parameters similar to those of the examined steel. Baking of electrodes before welding was conducted at the temperature 380 °C during 1 hour. This kind of welding electrodes was recommended by the authors after researches [16] for welding of 10KhSND steel in the conditions of negative temperatures below —40 °C.

Single manual arc butt welding was carried out by electrodes with diameter 2.5 and 4.0 mm, using direct current with reverse polarity, at the ambient temperatures +20, –15 and –35 °C. When preparing for welding, a groove imitating V-shaped preparation of edges was cut in plate middle, with a rake angle 30° and truncation 2 mm. Obtained preparation of edges was close to the sizes determined by the regulating document for butt welding of plates with thickness 14 mm. The plates were fixed before welding in a jigging fixture, for lowering deformations. Plates and jigging fixture were held in the cold conditions during 24 hours before welding of samples at negative temperature. Welding of samples was conducted via 5 passes (**Fig. 1**), with cooling down between them to the temperature ~150 °C. According to the research [17], the temperature of seam and heat-affected zone should be within the range from +80 °C to +250 °C before the beginning of each welding pass. The temperature of seam and heat-affected zone was measured by pyrometer after each pass. The root pass was carried out in such way, that electrode melting does not stop above a thermocouple. The main power engineering parameters (welding current and arc voltage) were registered using AWR-224MD recorder. Welding time and seam length were fixed to assess welding speed. The parameters of the welding operation for the samples are presented in the **Table 1**.

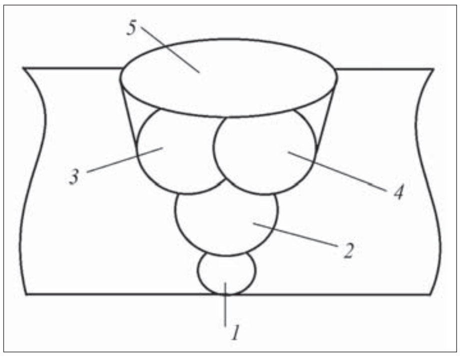

Fig. 1. The scheme of layers' location
(*1* — root layer; *2, 3* and *4* — filling layers; *5* — facing layer)

The principal scheme of device for recording of welding thermal cycles is presented in the **Fig. 2**. The block scheme consists of the following main components: smoothing condensers, microcontroller Arduino Nano 3.0, analogue and digital converter ADS1115, resistor, environment sensor, measuring thermocouples.

Thermoelectric converters (thermocouples) DTPK031-1.2/0.5/1 and DTPS021.1O-0.5/0.20 with open contact, produced by OVEN company, were used for examination of heat distribution at plates during welding in the conditions of naturally low and ambient temperatures. The first grade is a chromel-alumel thermocouple (type K) with diameters 1.2 and 1.2 mm. The second grade is a platinum-platinum/rhodium thermocouple (type S) with diameters 0.5 and 0.5 mm. Use of these thermocouples is stipulated by their high range of operating temperatures (up to +1372 °C for chromel-alumel thermocouples and up to +1768 °C for platinum-platinum/rhodium thermocouples) [18]. Before measuring operations, each thermocouple and assembled devices were preliminarily

Table 1. Parameters of the welding operation for the samples

No. of sample and welding temperature, (T, °C)	Welding passes	Average value		Welding rate V_{wel}, m/h	Weld heat input Q, kJ/m
		Current I, A	Voltage U, V		
1 +20	1 – root	96	23,5	5,75	1063
	2 – filling	164	24,2	7,76	1381
	3 and 4 – filling	164	25,6	16,67	680
	5 – facing	164	25,0	6,37	1734
2 –15	1 – root	96	26,2	6,75	1000
	2 – filling	162	25,4	8,94	1248
	3 and 4 – filling	162	26,5	13,50	860
	5 – facing	163	26,4	6,18	1875
3 –35	1 – root	95	27,1	6,79	1027
	2 – filling	162	24,4	9,00	1185
	3 and 4 – filling	163	23,9	13,21	794
	5 – facing	162	23,54	5,26	1959

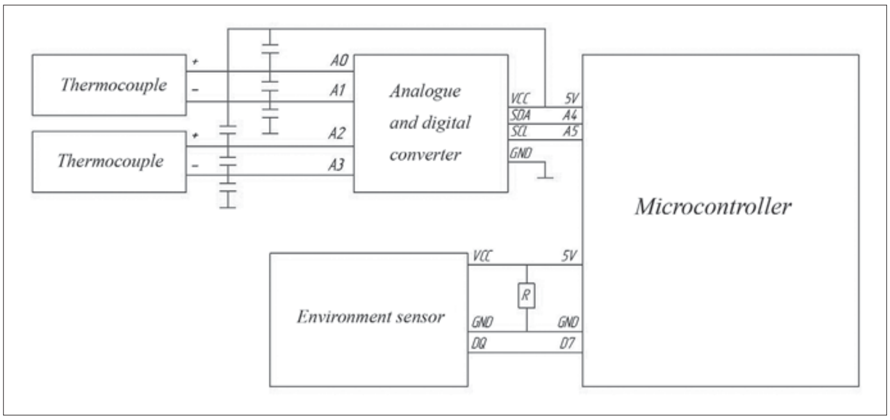

Fig. 2. Principal scheme of device for measuring and recording of welding thermal cycles

tested in the laboratorial muffle furnace Nabertherm Model L9/11/S27 up to the temperature 800 °C. Measuring cables and thermocouples were located at the ambient temperature during measuring of welding temperature cycle in the conditions of climatic low temperatures. The temperature and time values were transferred to a monitor and saved as a text file. The software part of the device allows recording of the temperature data from 0 °C and higher. Four thermocouples were mounted in each plate from their bottom surface, under root seam, according to the scheme displayed in the **Fig. 3**. Junctions of thermocouples were calked in prepared holes with diameters 2 and 3 mm.

Hardness measuring by Vickers of the welded joints areas was carried out using a hardness meter AFFRI 206RTD, with the load 588 N (60 kgf), according to the GOST 2999-75. Measuring of print diagonals was conducted using metallographic microscope NIM with the image visualization system on the base of digital specialized high-resolution camera with software for qualitative analysis of metal structure images «Image Expert Pro 3». Hardness was measured in a transversal

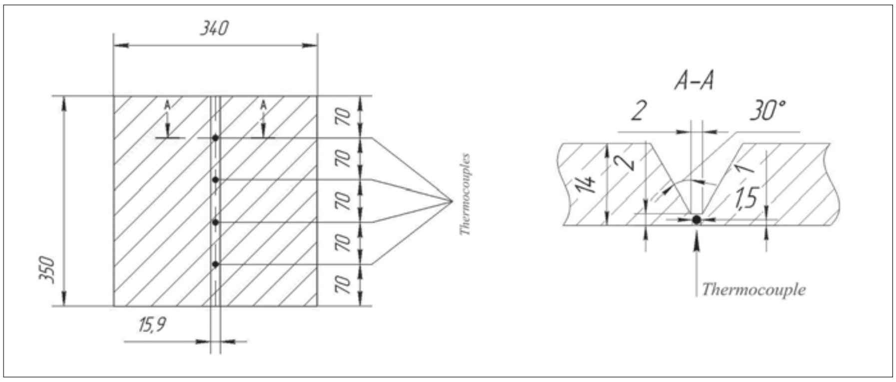

Fig. 3. Scheme of location of thermocouples during temperature measuring

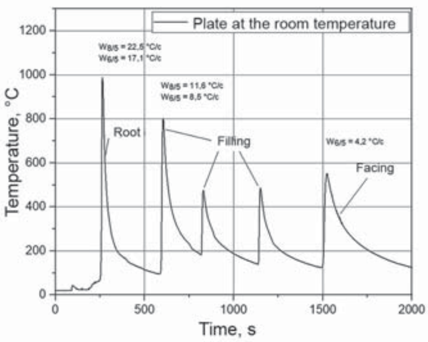

Fig. 5. Thermal cycles with a thermocouple located in the sample No. 1; welding is conducted at the room temperature

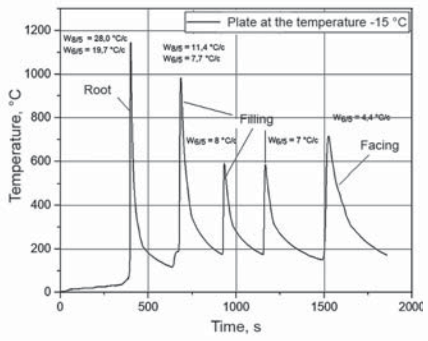

Fig. 6. Thermal cycles with a thermocouple located in the sample No. 2; welding is conducted at the temperature −15 °C

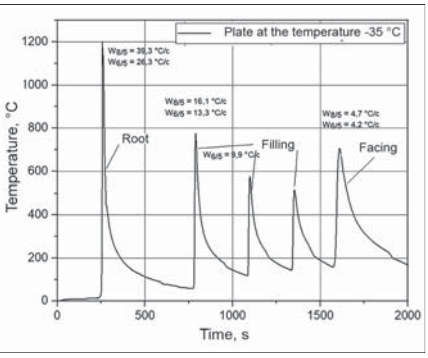

Fig. 7. Thermal cycles with a thermocouple located in the sample No. 3; welding is conducted at the temperature −35 °C

polished section of welded joints for the samples No. 1 and No. 3 along three lines, their location is shown in the **Fig. 4**.

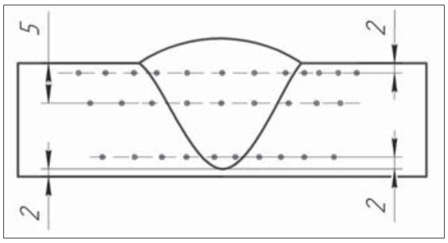

Fig. 4. Scheme of hardness measuring by Vickers of the welded joints areas

Research results and discussion

Comparison of heat input during welding of plates displayed that this indicator for root passes is practically equal for all samples, they differ within the range 2–6 % (see Table 1). Larger difference of heat input between passes is observed for filling and facing layers, with their maximal values up to 21 % and 11.5 % respectively. But in general, total heat input during welding of samples differs within relatively narrow range 2–5 %.

Based on the measuring data of thermocouples, the thermal cycles for multi-pass welding of samples were built. It can be seen that maximal temperatures of thermal cycles depend on weld heat input and built-up layer distance from the fixed measuring point. Thermal cycles after welding at the ambient temperatures +20, –15 and –35 °C are shown in the **Fig. 5–7**. The average cooling rates within the temperature range 600–500 °C ($W_{6/5}$) and 800–500 °C ($W_{8/5}$), as well as the average cooling time within the temperature range 600–500 °C ($W_{8/5}$) and 800–500 °C ($W_{3/2}$) are displayed in the **Table 2**. It should be noted that cooling rate and cooling time values were determined only for those thermal cycles, where the temperature reached the above-mentioned ranges.

Welding of samples was carried out without preliminary heat, thereby maximal cooling rate for all samples is observed during conduction of the first pass, while the consequent passes cooled more slowly due to automatic heating (see Table 2). It corresponds to currently used points of view for heat distribution during multi-pass welding [19].

Based on the results of measurements, cooling rate increase during welding of a root pass in the conditions of negative ambient temperatures was revealed. The average cooling

Table 2. The average cooling rate and cooling time values for thermal welding cycles for the samples

No. of sample	Welding temperature (*T*, °C)	No. of thermal cycle	$W_{6/5}$ (°C/s)	$W_{8/5}$ (°C/s)	$t_{8/5}$ (s)	$t_{3/2}$ (s)
1	+20	1	18.4	24.6	12.4	34.9
		2	8.7	12	25.3	86.1
		3	–	–	–	95.1
		4	–	–	–	68.0
		5	4.9	–	–	139.8
2	–15	1	19.5	28.7	11.2	30.2
		2	9.3	13.9	22.3	81.0
		3	9.1	–	–	91.0
		4	7.1	–	–	111.1
		5	4.7	–	–	137.8
3	–35	1	24.9	36.7	8.4	18.5
		2	13.5	17.9	16.7	70.1
		3	11.1	–	–	68.1
		4	–	–	–	72.6
		5	4.3	5.9	43.7	138.5

Table 3. Average hardness values in the welded joints areas

No. of sample	Welding temperature, °C	Average hardness values, HV60		
		SM	HAZ	BM
1	+20	229±5.2	192±6.9	220±4.4
3	–35	231±5.4	196±9.8	221±4.7

rate $W_{8/5}$ at welding temperatures –35, –15 and +20 °C made 36.7 °C/s, 28.7 °C/s and 24.6 °C/s respectively. The values of average cooling rates $W_{6/5}$ was smaller than $W_{8/5}$ by 25–32 %, and they also increase when welding temperature decreases. Thus, increase of cooling rates $W_{8/5}$ and $W_{6/5}$ at the temperature –15 °C was 15 % and 6 %, while the same parameters at the temperature –35 °C was 49 % and 35 % respectively.

When welding the second layer, the values of cooling rates $W_{8/5}$ and $W_{6/5}$ decreased practically by two times in comparison with the root layer, with reserving the tendency of their increase with reduction of a welding temperature (see Table 2). The average cooling rates of the second pass made (depending on a sample) 12.0, 13.9 and 17.9 °C/s ($W_{8/5}$) and 8.7, 9.3 and 13.5° C/s ($W_{6/5}$). During the following passes, the average cooling rates decrease from layer to layer. Minimal cooling rates are observed for facing layers, where $W_{6/5}$ was equal to 4.9 °C/s, 4.7 °C/s and 4.3 °C/s for the samples Nos. 1–3 respectively. Additionally, it was found out that cooling rate at the room temperature (sample No. 1) is higher than that for the samples No. 2 and No. 3. It is explained by higher weld heat input values in welding of facing layers of the samples No. 2 and No. 3 (see Table 1).

According to the data [2, 20], low ambient temperature during welding has serious effect on duration of welding seam metal cooling within the temperature range from 300 to 100 °C. Long cooling within this temperature range promotes more complete hydrogen extraction from a seam, what supports decrease of possibility of cold cracks forming [20]. Owing to cooling of a seam and a heat-affected zone between the passes to 150 °C, the cooling time was fixed within the temperature range from 300 to 200 °C ($t_{3/2}$). Based on the measuring results, $t_{3/2}$ values differ mostly essentially in welding of root passes (see Table 2). So, $t_{3/2}$ for the sample No. 1 is larger than that for the sample No. 3 by 1.9 times. As for the consequent passes, the values of $t_{3/2}$ for different samples vary slightly due to automatic heating. However, their cooling time increases essentially (by 2 times and more) and depends on weld heat input and preliminary heating temperature.

Welded joints of the samples No. 1 and No. 3 were examined for hardness after welding of plates. As soon as the hardness values in measuring points in a separate area of a welded joint does not vary substantially relating to the measuring lines for both samples (see Fig. 4), the measuring results were averaged in the following way: seam metal (SM). heat-affected zone (HAZ) and basic metal (BM). The average hardness values in welded joints areas with confidence range 95 % are presented in the **Table 3**. hardness of BM and SM was approximately 220 HV and 230 HV respectively, while the lowest hardness value for both samples was revealed in HAZ: 192 HV for the sample No. 1 and 196 HV for the sample No. 3.

Thermal effect during welding led to hardness decrease in HAZ of plate welded joints, what characterizes steel structure varying. Hardness decrease in HAZ (in comparison with BM) depends not only from the effect of welding thermal cycle, but also from initial steel state. Mechanical properties of steel 10KhSND are directly connected with the procedures of theat treatment and thermomechanical processing [21]. The examined rolled sheets were subjected to heat treatment according to the GOST 6713-2021 (quenching with high tempering), what provides high mechanical properties [21], which are required for operation at the calculated temperature down to –50 °C. After welding in HAZ, a structure with lower hardness (smaller than that in BM by 11–12 %) was formed. At the same time, comparison of the data revealed the small, but statistically significant SM hardness increase (231±5.4 HV against 229±5.2 HV) and HAZ hardness increase (196±9.8 HV against 192±6.9 HV) for the sample, which was welded at the temperature –35 °C, in comparison with the sample, which was welded at the temperature +20 °C.

Conclusions

1. It was confirmed experimentally that decrease of the ambient temperature from +20 °C to –35 °C led to essential increase of cooling rate for a welded joint. Maximal rise of cooling state (up to 49 %) is observed during the root pass within the temperature range 800–500 °C, what is connected with intensive heat withdrawal in the conditions of extra low temperatures.

2. It was established that consequent passes in the process of multi-pass welding are characterized by decrease of a cooling rate due to the effect of automatic heating. However, even in this case, at the temperature –35 °C, cooling rate in the second pass is higher than that at the room temperature by up to 50 %, what confirms necessity of taking into account external conditions during development of welding technologies.

3. The obtained data confirm that cooling time within the temperature range 300–200 °C decreases by 2 times in comparison with the room temperature (+20 °C) during welding of a root seam in the conditions of negative temperatures (down to –35 °C).

4. Automatic heating during multi-pass welding allows providing significant increase of cooling time for welded joints, which were produced at various ambient temperatures.

5. Hardness decrease by 11–12 % in comparison with basic metal was noted in the heat-affected zone (HAZ); it was stipulated by varying 10KhSND steel microstructure under the effect of thermal cycles. In this case, welding at the temperature –35 °C leads to statistically significant (though slight) seam metal hardness increase in HAZ.

6. The result of this research widen scientific apprehensions on thermal processes during welding in the conditions of negative temperature and form and integral picture about thermal cycles during multi-pass welding f steel in the conditions of cold climate. The obtained data can be used for improvement of welding technologies in the North and Arctic regions, what promotes rise of service life and reliability of welding constructions.

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REFERENCES

1. Gavrilova M. K. Climates in the cold regions of the Earth. Yakutsk : Izdatelstvo SO RAN. 1998. 206 p.
2. Larionov V. P. Electric arc welding of construction in the northern variant. Novosibirsk : Nauka. 1986. 253 p.
3. Kou S. Welding metallurgy. John Wiley & Sons, Hoboken, New Jersey, 2003. 461 p.
4. Matsuda F., Fukada Y., Okada H., Shiga C. Review of mechanical and metallurgical investigations of martensite-austenite constituent in welded joints in Japan. *Welding in the World*. 1996. Vol. 37. No. 3. pp. 134–154.
5. Olshanskaya T. V., Fedoseeva E. M. Choiced of the main criteria of a thermal cycle for predicting methods for welded seam structure during elecgtron-beam welding. *Vestnik Permskogo natsionalnogo issledovatelskogo politekhnicheskogo universiteta. Mashinostroenie, materialovedenie*. 2019. Vol. 21. No. 2. pp. 73–81. DOI: 10.15593/2224-9877/2019.2.09.
6. Efimenko L. A., Kapustin O. E., Ramus A. A. et al. Control of Softening Processes in the Heat-Affected Zone During Welding of High-Strength Steels. *Met. Sci. Heat Treat. 2016*. Vol. 58. pp. 435–441. DOI: 10.1007/s11041-016-0031-7.
7. Kumar R., Arya H. K., Saxena R. K. Experimental Determination of Cooling Rate and its Effect on Microhardness in Submerged Arc Welding of Mild Steel Plate (Grade c-25 as per IS 1570). *J. Material Sci. Eng.* 2014. Vol. 3. pp. 138. DOI: 10.4172/2169-0022.1000138.
8. Keehan E., Zachrisson J., Karlsson L. Influence of cooling rate on microstructure and properties of high strength steel weld metal. *Science and Technology of Welding and Joining*. 2010. Vol. 15. pp. 233–238.
9. Karkhin V. A. Thermal processes during welding. SPb. : Izdatelstvo Politekhnicheskogo universiteta. 2015. 572 p.
10. Efimenko L. A., Elagina O. Yu., Vyshemirskiy E. M. et al. Conventional and prospective steels for construction of main gas and oil pipelines. M. : Logos. 2011. 316 p.
11. Davis C. L., King J. E. Cleavage initiation in the intercritically rehated coarse-grained heat-affected zone: Part I. Fractographic evidence. *Metall. Trans.* A. 1994. Vol. 25A. pp. 563–573.
12. Stepanov P. P. Study of impact toughness for pipe steels after imitation of thermal welding cycles and welded seams of large diameter pipes. *Stal.* 2022. No. 10. pp. 42–49.
13. Hamada M. Control of strength and toughness at the heat affected zone. *Welding International*. 2003. Vol. 17. No. 4. pp. 265–270.
14. Ammosov A. P. Thermal deformation processes and destruction of welded joints. Yakutsk : YaF SO AN SSSR. 1988. 136 p.
15. Golikov N. I., Sannikov I. I., Semenov S. V., Ivanov M. A. Thermal cycles, structure and properties of fixed joints made of structural steels during welding in the conditions of extremal coldness. *Prirodnye resursy Arktiki i Subarktiki*. 2024. Vol. 29. No. 3. pp. 479–492. DOI: 10.31242/2618-9712-2024-29 3-479-492.
16. Golikov N. I., Saraev Yu. N., Sidorov M. M. et al. Study of possibility of use of coated electrodes UONI 13/moroz in welding at the negative ambient temperatures. *Svarka i diagnostika*. 2024. No. 3. pp. 30–35.
17. Company's standard. STO-GK “Transstroy” – 005-2018. Steel constructions of bridges. Technology of assembly welding. M. : AO TsNIIS. 2019. 148 p.
18. Garsiya V. Temperature measuring: theory and practice. *Sovremennye tekhnologii avtomatizatsii*. 1999. No. 1. pp. 82–87.
19. Theory of welding processes: a manual for high schools. Edited by Nerovnyi V. M. M. : Izdatelstvo MGTU im. N. E. Baumana. 2007. 752 p.
20. Sleptsov O. I., Mikhailov V. E., Petushkov V. G. et al. Increase of strength of welded constructions of the North. Novosibirsk : Nauka. 1989. 223 p.
21. Bannykh I. O., Blinov V. M., Kunitsyn G. A. et al. Structure and mechanical properties of sheet metal made of the bridge steel 10KhSND after heat treatment and controlled rolling with accelerated cooling. *Dorogi i mosty*. 2024. No. 51/1. pp. 215–238.