Influence of low temperature on structure and impact strength of structural steels welded joints

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Abstract. The article is devoted to the study of the relationship between climatic conditions of construction, installation and repair during the operation of industrial technical systems and the structure and properties of welded joints of structural steels. It has been established that the main technological factor affecting the crystallization of the weld metal from the melt is the heat input transmitted by the heating source - an electric arc, during welding at all intervals of the formation of one-piece joints. The research results made it possible to justify the conditions under which the formation of one-piece compounds occurs. The frequency ranges of controlled heat input, that maintain a specified set of welded joints mechanical properties are determined.

1. Introduction

Features of the construction, installation and repair of oil and gas facilities in extreme climatic conditions of the Far North and the Arctic are associated with the need for welding at low ambient temperatures. In the process of welding at low temperatures, the cooling and crystallization rates of the metal of the weld pool increase, which has a significant effect on the structure and mechanical properties of the welded joint [1, 2]. Based on the foregoing, it is necessary to develop a special welding technology that is effective in welding at low temperatures, which is an urgent scientific and technical task, the achievement of the goal of the work depends on the solution of this task - improving the reliability and safety of equipment and structures used in the North and the Arctic.

A promising direction, developed within the framework of the formulated goal, may be the use of pulsed welding processes [3]. Their advantages over those traditionally used are the ability to provide controlled heat input at the stages of controlling structural-phase transformations in the weld metal and the heat-affected zone due to periodic changes in the welding current [4]. It is known that the amount of input heat input during welding processes affects the microstructural and mechanical properties of the welded metal [5-7]. The study of this effect, for example, the microstructural features of the weld metal (WM) and the heat-affected zones (HAZ) of welded joints of pipe steels, has been the subject of work by many authors [8–10], including their relationship with the mechanical properties of the welded joints [11–14]. However, most of the studies related to the study of the microstructural state of weld joint zones have been performed for structures manufactured and operated under conditions of positive ambient temperatures.
2. Research material and equipment

The structural steels used in this study were 09G2S and St3sp grade steels, and their chemical compositions are presented in Tables 1 and 2. The new grades of domestic electrodes LB-52TRU LLC SPC "Welding materials", Krasnodar) and UONI 13/Moroz (LLC "High Technologies", Moscow) were used in the welding process. The list of used electrodes, their chemical composition and mechanical properties are shown in Table 3.

On plates with dimensions of 200x300x12 mm from 09G2S steel and 300x500x7.5 mm from St3sp steel, bevels with a bevel angle of (25 ± 2)°, a dullness of 2 mm and a gap of 1.6 mm for arc welding of a butt joint according to GOST 5264-80 are applied. Structural elements and their sizes, symbols are given in Table 4.

Table 1. Chemical composition (wt., %) and mechanical properties of 09G2S steel according to 19281-2014 state standard

|   | C   | Si  | Mn  | Cr  | Ni  | S   | P    | As  | Toughness, (U-notch) [J/cm²] | TS, [MPa] | Elongation, [%] |
|---|-----|-----|-----|-----|-----|-----|------|-----|------------------------------|------------|-----------------|
|   | <0.12 | 0.5-1.0 | 1.3-1.7 | <0.3 | <0.035 | <0.03 | <0.12 | <0.008 | <0.3 | ≥34 | ≥490 | ≥21 |

Table 2. Chemical composition (wt., %) of St3sp steel according to 19281-2014 state standard

|   | C    | Si   | Mn   | Cr   | Ni   | S    | P    | Cu  | Toughness, (V-notch) [J/cm²] | TS, [MPa] | Elongation, [%] |
|---|------|------|------|------|------|------|------|-----|-------------------------------|------------|-----------------|
|   | 0.14-0.22 | 0.15-0.30 | 0.40-0.65 | ≤0.30 | ≤0.30 | ≤0.04 | ≤0.05 | ≤0.30 | - | bal. |

Table 3. Chemical composition (wt., %) and mechanical properties of welding electrodes

| Electrode          | C    | Si   | Mn   | Cr   | Ni   | Mo  | S    | P    | Toughness, (V-notch) [J/cm²] | TS, [MPa] | Elongation, [%] |
|--------------------|------|------|------|------|------|-----|------|------|-------------------------------|------------|-----------------|
| UONI 13/Moroz      | 0.075 | 0.3  | 0.7  | 2.8  | -    | 0.010 | 0.017 | 210  | ≥49 at -30 °C               | 540        | 29              |
| LB-52TRU           | 0.09  | 0.42 | 0.9  | -    | -    | 0.017 | 0.020 | ≥49 at -30 °C               | 540        | 29              |

Table 4. Design elements and their dimensions (5264-80 State Standard)

| Weld joint type | Design elements | S = S_t | e | g | Nominal Deviation | Nominal Deviation |
|-----------------|-----------------|---------|---|---|------------------|------------------|
| C17             | Butt joint edge preparation | 12 | ±2 | 0,5 | +1.5 | -0.5 |
|                 | Weld joint      | 6       |  |   |                  |                  |

One-sided welding of plates made of 09G2S steel was carried out in three passes by electrodes of the LB-52TRU and UONI 13/Moroz diameters: 3,0 mm for forming the root layer and 4,0 mm for forming the filling and facing layers (Fig. 1, b). For research, the following welding modes were selected and performed: direct current (DCW) and current modulation with a welding frequency of 1.67 Hz (PCW-1.67) and 5 Hz (PCW-5) – an adaptive pulsed-arc welding method. The plates were welded at naturally low climatic temperatures (-45 °C), and to compare the results of studies, DC welding was performed at room temperature.
One-sided welding of plates made of St3sp steel was carried out in two passes at negative (-40 °C) and positive (+20 °C) ambient temperatures with the use of domestic electrodes LB-52TRU with complete cooling of the root pass. Welding was carried out at direct current (DCW) and current modulation with a welding frequency of 1.67 Hz (PCW-1,67).

For welding, inverter welding power sources were used: FEB-315 "MAGMA" for adaptive-pulse welding and NEON VD-315 for DC welding. Modes and parameters of welding processes are presented in Tables 5 and 6.

During the welding process, the main energy parameters (current and arc voltage) were recorded using the AWR-224MD welding process recorder. During the technological experiment, the welding time was estimated and the average heat input was calculated in accordance with the generally accepted methodology.

### Table 5. Marking of welded plates, conditions and modes of welding steel 09G2S

| Marking of welded plate, No. | Ambient temperature, °C | Electrode   | Welding pass, electrode diameter, mm | Welding mode | Current parameters (Pulse Current (Ip, A), Background Current (Ib, A) and Voltage (U, B)) | Heat Input, kJ/m |
|-----------------------------|--------------------------|-------------|-------------------------------------|--------------|---------------------------------------------------------------------------------|------------------|
| 1                           | -45                      | UONI 13/    | 1) Root – 3                        | PCW-1,67     | 1) Ip=135, Ib=50, U=25,7                                                         | 1) 984           |
|                             |                          | Moroz       | 2) Fill – 4                        |              | 2) Ip=200, Ib=60, U=26,3                                                          | 2) 1527          |
|                             |                          |             | 3) Cover – 4                       |              | 3) Ip=200, Ib=60, U=26,3                                                          | 3) 1805          |
| 2                           | -45                      | UONI 13/    | 1) Root – 3                        | PCW-5        | 1) Ip=120, Ib=50, U=24,5                                                          | 1) 665           |
|                             |                          | Moroz       | 2) Fill – 4                        |              | 2) Ip=180, Ib=60, U=23,1                                                          | 2) 1318          |
|                             |                          |             | 3) Cover – 4                       |              | 3) Ip=180, Ib=60, U=23,1                                                          | 3) 1891          |
| 3                           | -45                      | UONI 13/    | 1) Root – 3                        | DCW          | 1) I=98, U=23,6                                                                   | 1) 973           |
|                             |                          | Moroz       | 2) Fill – 4                        |              | 2) I=154, U=24,4                                                                  | 2) 1681          |
|                             |                          |             | 3) Cover – 4                       |              | 3) I=154, U=24,4                                                                  | 3) 1698          |
| 4                           | +20                      | UONI 13/    | 1) Root – 3                        | DCW          | 1) I=98, U=26,2                                                                   | 1) 804           |
|                             |                          | Moroz       | 2) Fill – 4                        |              | 2) I=145, U=25,5                                                                  | 2) 1489          |
|                             |                          |             | 3) Cover – 4                       |              | 3) I=146, U=25,0                                                                  | 3) 1796          |
| 5                           | -45                      | LB-52TRU    | 1) Root – 3                        | PCW-1,67     | 1) Ip=136, Ib=50, U=28,1                                                          | 1) 794           |
|                             |                          |             | 2) Fill – 4                        |              | 2) Ip=200, Ib=60, U=23,6                                                          | 2) 1529          |
|                             |                          |             | 3) Cover – 4                       |              | 3) Ip=200, Ib=60, U=22,7                                                          | 3) 2008          |
| 6                           | -45                      | LB-52TRU    | 1) Root – 3                        | DCW          | 1) I=98, U=25,5                                                                   | 1) 804           |
|                             |                          |             | 2) Fill – 4                        |              | 2) I=145, U=25,5                                                                  | 2) 1489          |
|                             |                          |             | 3) Cover – 4                       |              | 3) I=146, U=25,0                                                                  | 3) 1796          |
| 7                           | +20                      | LB-52TRU    | 1) Root – 3                        | DCW          | 1) I=98, U=26,2                                                                   | 1) 804           |
|                             |                          |             | 2) Fill – 4                        |              | 2) I=145, U=25,5                                                                  | 2) 1489          |
|                             |                          |             | 3) Cover – 4                       |              | 3) I=146, U=25,0                                                                  | 3) 1796          |
| 8                           | +20                      | LB-52TRU    | 1) Root – 3                        | PCW-1,67     | 1) Ip=136, Ib=50, U=29,5                                                          | 1) 743           |
|                             |                          |             | 2) Cover – 4                       |              | 2) Ip=200, Ib=60, U=24,5                                                          | 2) 1404          |

### Table 6. Marking of welded plates, conditions and modes of welding steel St3sp

| Marking of welded plate, No. | Ambient temperature, °C | Electrode  | Welding pass, electrode diameter, mm | Welding mode | Current parameters (Pulse Current (Ip, A), Background Current (Ib, A) and Voltage (U, B)) | Heat Input, kJ/m |
|-----------------------------|--------------------------|------------|-------------------------------------|--------------|---------------------------------------------------------------------------------|------------------|
| 1                           | +20                      | LB-52TRU   | 1) Root – 3                        | PCW-1,67     | 1) Ip=136, Ib=50, U=29                                                            | 1) 707           |
|                             |                          |            | 2) Cover – 4                       |              | 2) Ip=200, Ib=60, U=25                                                            | 2) 1475          |
| 2                           | +20                      | LB-52TRU   | 1) Root – 3                        | DCW          | 1) I=94, U=28,5                                                                  | 1) 719           |
|                             |                          |            | 2) Cover – 4                       |              | 2) I=143, U=23,4                                                                  | 2) 1253          |
| 4                           | -40                      | LB-52TRU   | 1) Root – 3                        | PCW-1,67     | 1) Ip=136, Ib=50, U=29                                                            | 1) 743           |
|                             |                          |            | 2) Cover – 4                       |              | 2) Ip=200, Ib=60, U=24,5                                                          | 2) 1404          |
Microstructures of welded joints were examined by a high-resolution scanning electron microscope (JEOL JSM-7800F). To analyze the structure, a cross-section of the welded joints was made and then the specimens were mechanically-polished and etched in a 4% solution of nitric acid in ethanol. Structural studies were carried out at the middle level of the cross section of the welded joint (specimens) with a 0.5 mm research step.

Charpy impact tests were conducted on standard-size Charpy V-notch bars at -60, -40, -20 and 20 °C by a pendulum impact tester (RKP 450, Zwick Roell). Samples of V-shaped incisions in the weld metal and fusion zone were made according to State Standard 6996-66, type IX. The samples were cooled to the required temperatures using the Lauda climate chamber.

3. Results of the experiments and discussion

Welding of low alloy steel 09G2S. It was found that when welding at low temperatures (-45 °C) with an average heat input of 1440 kJ/m, the proportion of bainite in the HAZ is from 16 to 45 %. In the HAZ regions, a ferritocarbide mixture is observed, and bainite is observed in the region up to 2.5 mm from the fusion line. The size of ferrite grains is on average 8-12 microns. When welding at positive temperatures (+20 °C) with an average heat input of 1335 kJ/m, the proportion of bainite in the HAZ ranges from 5 to 15 % in the area up to 1.5...2 mm from the fusion line. The structure of the HAZ consists of a ferritocarbide mixture, and the size of the ferrite grains at 2...4 mm is 1.5-3 times larger than when welding at low temperatures. At a distance of 3 mm from the fusion line and further, the carbide content decreases, and pearlite grains are formed.

Thus, a study of the structures of the HAZ of welded joints obtained by welding at low climatic ambient temperatures showed that in areas of incomplete melting and overheating, welding at -45 °C forms more finely dispersed ferritocarbide mixtures with a higher content of quenching bainitic structures (compared to welding at room temperature (Fig. 1). A broadening of the propagation zone of quenching structures (bainite) and carbides is observed.

According to the results of impact testing of HAZ of welded joints of 09G2S steel, it was found that an increase in the content of bainitic structures in the weld zone during cold welding does not lead to a significant decrease in KCV values in the test temperature range from -60...+20 °C. The impact strength of the fusion zones of samples welded at negative (-45 °C) and positive (+20 °C) temperatures using UONI-13/Moroz electrodes does not differ significantly (Fig. 2, a). A slight decrease in KCV is observed in the range of test temperatures of -40...-20 °C, performed by PCW-5 at -45 °C. This welding mode had the minimum average linear energy (1291 kJ/m), which led to the formation of quenching structures in the BWZ in the form of bainite up to 90%. For samples obtained by welding with LB-52TRU electrodes at a temperature of -45 °C, the toughness
of the fusion zones in the test temperature range from -40...+20 °C is greater than that performed at room temperature (Fig. 2, b). The increase in KCV values is associated with the formation of a finer-grained structure in the HAZ of 09G2S steel compared to room temperature and the content of bainite in the HAZ up to 30 %.

Figure 2. Dependence of impact strength on test temperature of a specimen with a V-shaped notch in a HAZ made of 09G2S steel obtained by welding using electrodes of (a) UONI 13/Moroz and (b) LB-52TRU electrodes:
1 – PCW-1,67 (-45 °C); 2 – PCW-5 (-45 °C); 3 – DCW (-45 °C); 4 – DCW (+ 20 °C)

The study of the influence of the current modulation frequency in adaptive pulse-arc welding on the HAZ structure during welding at low temperatures showed that when welding with a current modulation frequency of 5 Hz (SMT-5) and direct current (DC), the HAZ structures do not differ significantly from each other. The most favorable structure of the HAZ of the welded joint is obtained by pulsed arc welding with a frequency modulation current of 1.67 Hz using an LB-52TRU electrode. At the same time, welding at -45 °C was carried out with an increased average linear energy of 10% compared to room temperature, as well as with an increased by 15-20 % linear energy of the process of welding of the facing weld. According to the results of impact tests of these welded joints, the highest characteristics of impact strength were established (Fig. 2, b).

Welding of low-carbon steel St3sp. According to the test results, curves of the impact toughness of the WM (KCV) versus test temperature were constructed (Fig. 3).

Figure 3. Dependence of impact strength on the test temperature of a sample with a V-shaped notch in a WM obtained by welding using LB-52TRU electrodes under room (a) and negative temperature (b) conditions: 1 – PCW; 2 – DCW

From Fig. 3 (a, b) it can be seen that at room temperature, the average values of the impact toughness of the WM obtained by DCW under both welding conditions are higher by 48 J/cm² and 37 J/cm², respectively, than with PCW. Perhaps this is due to a higher linear energy of 220 kJ/m with PCW of the facing layer than with DCW.

The average values of the impact toughness of the WM at PCW are higher by 22 J/cm² than at DCW in the transition test temperature (-20 °C) to lower. When the test temperature was lowered, starting from -40 °C, a transition from a viscous to a brittle state was detected. A sharp drop in the
average values of impact strength during temperature tests from -40 °C and below indicate embrittlement of the WM obtained by PCW and DCW, regardless of the welding conditions.

Studies of the microstructure of the weld metal of all samples showed that the weld structure in the central part has a columnar structure with orientation of crystallites in the direction of heat removal and consists of ferrite, perlite, and bainitic structure (Fig. 4).

Figure 4. Microstructure of the weld metal of welded joints made under room (a, b) and negative temperatures (c, d) at the level of the middle of the weld cross-section, x1000:

a, c – PCW; b, d – DCW

In general, the formation of quenching structures in the weld metal led to a decrease in toughness and embrittlement at low test temperatures.

According to the test results, curves of the impact strength of the HAZ (KCV) versus test temperature were constructed (Fig. 5).

Figure 5. Dependence of impact strength on the test temperature of a sample with a V-shaped notch in a HAZ obtained by welding using LB-52TRU electrodes under room (a) and negative temperature (b) conditions: 1 – PCW; 2 – DCW

From Fig. 5 it can be seen that the average values of impact strength, regardless of the type and conditions of welding, are almost at the same level over the entire range of test temperatures. With a decrease in test temperatures from -20 °C, we observe a sharp drop in the average values of impact strength of HAZ.

The low impact toughness of the heat affected zone can be explained by the fact that the HAZ has a Widmanstett structure, where crystalline grains are randomly located, inside of which there are structure elements in the form of needles (Fig. 6). The growth of pearlite colonies also begins at the grain boundaries of austenite or excess ferrite. In the HAZ section of the welded joint, starting from the level of 0.5 mm and further, martensitic structures are formed. Also, under the considered regimes, the formation of bainitic structures along the boundaries of ferrite grains is observed.

Figure 6. The microstructure of the HAZ of welded joints made under room (a, b) and negative
temperatures (c, d), x1000: a, c – PCW; b, d – DCW

When welding low-carbon steel St3 at low temperatures compared with positive ambient temperatures, the volume fraction of quenching structures in the form of martensite increases significantly. On the whole, a comparison of the toughness values of welded joints made at different temperatures shows that there is a slight decrease in the toughness of MS and HAZ. This decrease is felt at test temperatures of -40...-60 °C.

4. Conclusion
Based on the results of the studies established:
1. The formation of the structure of welded joints is significantly affected by the ambient temperature at which the welding process is carried out. When welding at low temperatures, finer-grained structures are formed due to an increase in the cooling rate. But at the same time, the proportion of quenching structures in the form of martensite and bainite increases, which can lead to a certain decrease in the values of impact strength in the zones of the weld metal and thermal influence.
2. The highest impact strength values of the HAZ of the welded joint were obtained in pulsed-arc welding at low climatic ambient temperatures with a frequency modulation of 1.67 Hz.
3. With an increase in the modulation frequency of the welding current, the heat flux is averaged, and, at a frequency of 5 Hz, the structure of the HAZ of the permanent connection becomes the same as when welding in DC mode.
4. When welding in conditions of low climatic temperatures, up to -45 °C, steel 09G2S, an increase in heat input is required, compared with welding modes carried out at a positive temperature, in the range from 10 to 20 %. In this case, increased heat input during welding at low climatic temperatures compensates for the "cooling" effect of the ambient temperature, which contributes to the most rational cooling rate of the welded product, and, as a result, the formation of the required structural state of welded joints.

The studies made it possible to establish the areas of rational welding conditions depending on the climatic conditions of welding, installation and repair work, and also allowed to determine the most dominant criteria for their influence on the performance of structures. Thus, the ongoing research is an important stage of work aimed at improving the performance of welded metal structures in the oil and gas industry, operating in the North and the Arctic.

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