Investigation of the microstructure of the heat-affected zone of low-alloyed steel during pulsed arc welding under conditions of low climatic ambient temperatures

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Abstract. The development of a special technology of welding at low temperatures is an urgent scientific and technical challenge aimed at solving the problems of increasing the reliability and safety of products of equipment and structures operated under conditions of the North and the Arctic. One of the perspective technologies is pulsed arc welding. The structure of the heat-affected zones (HAZ) of welded joints produced by pulsed arc welding at an ambient temperature of 45 degrees Celsius below zero was studied. Two frequency modes were applied during modulated-current welding, and the results obtained were compared with the traditional method of manual arc welding with direct current. The features of the influence of the modulation frequency of the welding current and the temperature of the welding performance on the microstructure of the HAZ of 09G2S steel welded joints are revealed.

1. Introduction

In the regions of cold climate, the average annual ambient air temperatures are about 10 °C below zero and lower, and the period of negative temperatures lasts more than 210 days, so a significant amount of welding work during construction, installation and repair of structures is carried out at negative temperatures. Welding under conditions of low climate temperatures has its own characteristics associated with an increase in the cooling rate of welded joints [1]. As the cooling rate increases, the probability of formation of quenching structures increases, which can lead to brittle fracture of welded joints.

The metal of the near-weld zone is characterized by microstructural heterogeneity due to the gradient of temperature fields. The most problematic, in terms of providing a complex of properties, is the overheating area, which is formed as a result of thermal effects on the base metal [2]. Under the influence of high temperatures, an undesirable microstructural state is formed, which causes reduced cold resistance and embrittlement of the metal near the fusion line [3].

Improvement of the microstructural state of the HAZ of welded joints is possible using pulsed welding technologies [4, 5]. Pulsed welding technologies have significant advantages [4–9] and allow through programmable input of heat into the welded joint zone, control of the processes of melting and transfer of each drop of electrode metal, creation in the zones of welded joints of technical systems of a fine structure in the weld metal and HAZ, to significantly reduce the degree of residual deformations of welded joints.

The use of modulated current provides high efficiency control of the structure and properties of the weld metal when welding with current pulses of low frequency range from 5.0 Hz and below. However,
the question of the influence of the current modulation frequency, as well as the effect of changes in the ratios of the parameters of current pulses, its amplitude, duration, modulation depth, on the formation of the structure, requires further study. According to the work of [10], the most effective frequency range, which ensures the reduction of structural components in the zones of the welded joint when welding is modulated by the current of low-alloyed steels, ranges from 1 to 2.5 Hz.

Research purpose is to study the structure of the HAZ of welded joints of low-alloyed steel, made in two frequency modes of pulsed arc welding at negative ambient temperatures.

2. Materials and equipment
Rolling sheet of 09G2S low-alloy structural steel, corresponding to State Standard 19281-2014, as the most widely used in structures operated in the conditions of the North and the Arctic, was chosen as the material for research. Steel of this grade is well welded in a wide range of welding modes, regardless of the thickness of the welded elements and the ambient temperature. The chemical composition and mechanical properties of 09G2S steel are presented in Table 1.

For research, manual arc welding of samples with a single-V butt weld was made. Welding was carried out in three passes using LB-52TRU and UONI 13/Moroz electrodes with diameters: 3.0 mm to form the root layer and 4.0 mm to form the filling and facing layers. The chemical composition and mechanical properties of the used welding electrodes are shown in Table 2.

Inverter welding power sources were used for welding the samples: FEB-315 “MAGMA” for pulsed arc welding and NEON VD-315 for direct current welding. The following welding modes were selected for research:
- pulse-arc welding with a modulation frequency of the welding current of 1.67 Hz (MCW-1.67) at a welding performance temperature of −45 °C;
- pulse-arc welding with a modulation frequency of the welding current of 5 Hz (MCW-5) at a welding execution temperature of −45 °C;
- direct current welding (DCW) at a welding temperature of −45 °C;
- direct current welding (DCW) at a welding temperature of +20 °C.

The main energy parameters (arc current and voltage) during the welding process were recorded with 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 method. Heat inputs of welding the root layers were 660...980 kJ/m, and the filling and facing layers were 1320-2020 kJ/m.

**Table 1.** Chemical composition (wt%) and mechanical properties of 09G2S steel according to State Standard (GOST) 19281-2014

| C   | Si  | Mn  | Ni  | S   | P   | Cr | V   | N   | Cu  | As  | Toughness  | TS  | Elongation |
|-----|-----|-----|-----|-----|-----|----|-----|-----|-----|-----|-------------|-----|------------|
|     |     |     |     |     |     |    |     |     |     |     | (U-notch) [J/cm²] | [MPa] | [%]        |
| <0.1 | 0.5 | 1.3 | <0.03 | <0.0 | <0.1 | <0.00 | <0.0 | <0.0 | ≥34 at 70°C | ≥490 | ≥21        |
| 2   | 0.8 | 1.7 | 3    | 3    | 2   | 8   | 8   | 3    |                |      |            |

**Table 2.** Chemical composition (wt%) and mechanical properties of welding electrodes

| Electrode       | C   | Si  | Mn  | Ni  | Mo | S   | P   | Toughness (V-notch) [J/cm²] | TS  | Elongation [%] |
|-----------------|-----|-----|-----|-----|----|-----|-----|----------------------------|-----|--------------|
| UONI 13/Moroz   | 0.075 | 0.3 | 0.7 | 2.8 | -  | 0.010 | 0.017 | 210                        | 660 | 22.0         |
| LB-52TRU        | 0.09 | 0.42 | 0.9 | -   | -  | 0.017 | 0.020 | ≥49 at -30°C                | 540 | 29           |

Metallographic studies of the microstructures of welded joints in the HAZ were performed on a high-resolution scanning electron microscope with a Schottky cathode JEOL JSM-7800F. To analyze the structure, a cross-section of the welded joints was made and metallographic sections were prepared.
reveal the structure of the samples, chemical etching of the surface with a 4% solution of nitric acid in ethanol was used.

3. Research results and discussion
The microstructure of the base metal is a ferritic-pearlite mixture with a ratio of the volume fraction of structural components in the amount of 90/10 (ferrite/perlite) (Fig. 1). The average grain diameter of ferrite is about 6 microns. The base metal has a homogeneous polygonal structure.

![Figure 1. Microstructure of the base metal.](image)

The HAZ microstructures at the fusion line (FL) of welded joints at the level of the filling layer, obtained by weld with UONI 13/Moroz electrodes are presented in Fig. 2.

| Fusion Line (FL) | HAZ, 0.5 mm from the FL | HAZ, 1.0 mm from the FL |
|------------------|------------------------|------------------------|
| MCW -1.67 (-45°C)|                        |                        |
| MCW -5 (-45°C)   |                        |                        |
| DCW               |                        |                        |
The HAZ of the welded joints obtained at DCW (−45 °C) and MCW−5, on the fusion line and up to 1 mm from it, have a similar fine-needle microstructure consisting of ferrite, upper bainite and a small amount of lower bainite. In similar zones of the welded joint, obtained at the MCW−1.67 mode, a significantly different structure can be traced, consisting of a ferrite-carbide mixture, upper and lower bainite.

The structure of the HAZ of the specimen obtained at the DCW (+20 °C) differs significantly from the structure of the HAZ performed by the DCW (−45 °C). At the site of incomplete melting and at a distance of 0.5 mm from it, a ferrite-carbide mixture was found with a low content of bainite structure (Fig. 2).

Incomplete melting and overheating areas structure of the HAZ of welded joints obtained by welding with using electrodes LB-52TRU is a ferrite-carbide mixture with the presence of quenching structures of upper bainite (Fig. 3). The similarity of structural components of the HAZ of welded joints was revealed by MCW−5 and DCW (−45 °C), where the size of carbide components is larger than in the sample made by MCW−1.67.

The structure of the HAZ of the specimen performed at the DCW (+20 °C) significantly differs from the structure obtained at the DCW (−45 °C). At the zone of incomplete melting and at a distance of 0.5 mm from it, a ferrite-carbide mixture with a low content of bainite structure was found (Fig. 3).

According to the results of a calculated estimate, depending on the heat input of welding, it was found that under negative temperatures (at −45 °C), the cooling rate of the HAZ metal increases in the range of 30...70 % compared with a positive temperature (at +20 °C). The calculated estimate of the cooling rates during welding was performed according to the theory N. N. Rykalin. [14]. In this regard, in areas of incomplete melting and overheating of the HAZ of welded joints made under conditions of low climatic temperatures, the formation of quenching structures was detected.

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**Figure 2.** Microstructure of the HAZ of the welded joint at the level of the filling layer obtained using electrode UONI 13/Moroz.

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**Figure 3.** Microstructure of the HAZ of the welded joint at the level of the filling layer obtained using electrode LB-52TRU.
4. Conclusions
Analysis of the presented microstructures of welded joints zones, obtained during welding at direct current and in pulsed mode, shows that with an increase in the modulation frequency of the welding current, the heat input is equalized and, at a frequency of 5.0 Hz, the size of the HAZ becomes the same as during welding in DC mode. Apparently, this is due to the heat inertia of heat propagation from the heating source.

The study of the HAZ structures of 09G2S steel welded joints obtained by welding at different ambient temperatures showed that in zones of incomplete melting and overheating, welding at –45 °C forms ferritic-carbide mixtures with a certain content of quenching bainite structures that are more dispersed compared to structures at welding at room temperature.

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