Development of Mechanized Arc Welding Technology for High-strength Reinforcing Steel in a Reductive Carbon Monoxide Atmosphere

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Abstract. Modern methods of welding high-strength reinforcing steels were analyzed. Comparative studies of welded joints obtained using manual arc welding and welding in a reducing atmosphere of carbon monoxide were carried out. A chemical and metallographic analysis of welded joints was performed. It has been established that welded joints of microalloyed steels made at low temperatures may have reduced strength and viscous properties. The possibility of making welded steel joints using highly-efficient arc welding in a reducing medium of carbon monoxide was investigated. Welding modes have been selected to ensure the formation of a quality welded joint. Studies showed that the use of the proposed welding method in a reducing medium of carbon monoxide ensures full strength of the welded joint and the base metal.

1. Introduction
For a long time people used reinforcing steel of periodic profile A300 and A400 to produce welded reinforced structures. Thus, this reinforcing steel due to its high carbon content belongs to a limited welding type, and can’t be used at temperatures below -40°C. It should be noted that in most countries welded reinforcing steel containing more than 0.22% of carbon is not accepted [1]. Whereas, the carbon equivalent should not exceed 0.52 % [2].

There is an applicable Russian standard [3], which regulates the norms of chemical composition, mechanical properties and other standards in relation to reinforcing steel A500S. According to these requirements, the reinforcing steel is thermomechanically hardened, hot-rolled with micro-alloying or cold-worked. The production method and low limits of chemical composition are chosen by the manufacturer on the basis of weldability without softening (of loss of strength), plasticity, bending angle around the bar with a 3d diameter of at least 180°, as well as standard endurance and other indicators. At the same time it is allowed to use this reinforcing steel up to -50°C. Other regulatory documents providing the use of microalloyed steels for the reinforced concrete structures are being developed [4]. Whereas, it is allowed to use this reinforcing steel for the work in the Far North conditions [5, 6].

However, the authors noted some fractures of A500S reinforcing steel bars microalloyed with vanadium during installation of reinforced concrete in winter conditions. In the proposed work, the causes of brittle fracture were investigated, and the technology of arc welding of the studied steels was developed.
2. Scientific relevance
Microalloyed steels with carbonitride forming elements — vanadium and niobium — are widely used in the manufacture of sheet metal [7], pipes [8], and reinforcing bars [9]. The studies [10,11] showed that hot-rolled reinforcing 15GF steels have strength characteristics corresponding to class A-III (A400), high impact strength, as well as a good weldability. The site [12] recommends the use of class A600S microalloyed steels for all types of welding used in construction. According to [13], it is allowed to weld lattice (or framed) structures at temperatures up to -30°C, and it is recommended to preheat the metal up to 120 ... 160°C.

At the same time, the works [14, 15] showed that combined vanadium and niobium microalloying deteriorates weldability and resistance to brittle fracture due to thermal welding effects. The work [16] found a significant drop in the cold hardness of welded joints from vanadium microalloyed steels. The work [17] recommends excluding vanadium from the chemical composition of steels to ensure the viscous properties of welded joints. Thus, the issue of possible use of microalloyed steels in reinforced concrete structures at negative operating temperatures remains unclear. Since the replacement of A400 reinforcing steels with A500 leads to 10% cost savings, the need to develop an optimal welding technology for these steels is a very urgent task.

3. Research objective
Determine the causes of weld failure of A500S reinforcing bars, as well as develop technological methods to ensure full strength of the base metal and the welded joint.

4. Theoretical part
The construction and installation organization during its research provided design and engineering documentation, which indicated the use of A500S fittings in accordance with GOST 52544 [18]. According to marking, the reinforcing steel is weldable, hot rolled or thermos mechanically strengthened.

This GOST does not regulate the applicable steel grades, but only limits the content of elements. The chemical composition of the metal is shown in Table 1.

| Table 1. Chemical composition of steel and carbon equivalent value. |
|--------------------------|——|——|——|——|——|——|——|——|——|
| Element               | C  | Si  | Mn | V  | Cu | S  | P  | Carbon equivalent   |
| Max by GOST R52544    | 0.24 | 0.95 | 1.70 | --- | 0.50 | 0.050 | 0.055 | 0.52 |
| By the results of chemical analysis | 0.20 | 0.579 | 1.162 | 0.08 | 0.054 | 0.011 | 0.009 | 0.41 |

5. Practical relevance and experimental results
It is established that the studied material corresponds to 17GS steel.

Metallographic studies of welded joints obtained by manual arc welding (MMA technology) were carried out. The results are presented in Figure 1.
The reinforcing steel with metal banding of 2 pointed ferritic-pearlitic structures is observed. Due to high cooling rates microstructural heterogeneity with quenching structures is formed in the heat-affected zone. The metal hardness was 400 ... 470 HV. It is the presence of martensitic microstructure that causes the formation of cold cracks either during welding or within a few hours after it.

Usually, in order to avoid the formation of quenching structures, we use preheating, which is permitted during construction welding in accordance with [13]. The recommended temperature of 180°C cannot be precisely ensured when heated with a gas burner during installation in winter conditions. On the other hand, increasing the preheat temperature leads to a decrease in the cooling rate.

The effect of the cooling rate as a function of the heating temperature on the hardness of class A500S reinforcing steel during air cooling and negative ambient temperatures was investigated. The cooling rate means the cooling rate of a sample in the range of 800 ... 500°C. The results are shown in Figure 2a, and the thermo-kinetic cooling diagram is shown in Figure 2b.

![Figure 1. Microstructure of the welded joint made by MMA technology.](image)

![Figure 2. The effect of cooling rate on steel hardness (a) and steel microstructure (b).](image)

Samples with a simulated welding cycle (heating up to 1300°C and subsequent cooling under various conditions) were cut out for samples with a U-shaped notch. Finally, the dependence of impact strength on the cooling rate was obtained and shown in Figure 3. It was established that a decrease in the cooling rate below 10°C/s leads to a sharp decrease in the viscous properties of the metal.
Figure 3. The effect of sample cooling rate on the impact strength of A500S vanadium microalloyed reinforcing steel.

Tensile tests were performed according to [18] on welded joints after preheating on an R-50 tensile testing machine. A significant decrease in strength (up to 25%) of the welded joint was noted with the failure occurring in the base metal. Probably, overheating of the reinforcing steel led to metal softening and removed the effects of thermo-mechanical hardening.

Based on the above, it should be noted that the applied technology of welding A500S microalloyed vanadium fittings does not ensure the operational reliability of the welded joints made at negative air temperatures.

Welded joints were made using mechanized welding in a reducing carbon monoxide atmosphere (GMAW technology). Welding modes are given in [19]. As was shown in [20], the proposed mixture self-ignites during the contact with air oxygen. Thus, additional heat generation and metal heating by resulting gas flame occurs. The microstructure of the obtained welded joint is shown in Figure 4.

Figure 4. Reinforcing steel macrostructure (a), section 1 (b) and 2 (3).

Given microstructures are typical for low alloy steels. A sufficiently large grain size in the welded metal can be explained by the presence of silicon. Since, welding is carried out without stopping in several passes unlike the MMA technology, the heat-affected zone undergoes repeated recrystallization, leading to a decrease in hardness, grain refinement and the elimination of quenching structures. The hardness of the welded joint did not exceed 290 HV and the heat-affected zone - 260 HV. The ultimate tensile strength was 606.5 MPa, meeting [3] and [18] requirements.

The presence of non-metallic inclusions in the welded metal observed in all areas made in the proposed reducing atmosphere should be noted. Photos of microstructures with inclusions are shown in Figure 5.
Figure 5. Microstructure of the base metal (a), and the welded metal (b) and (c).

Analysis of the form and distribution of non-metallic inclusions suggests the occurrence of active metallurgical reactions. For theoretical studies of possible chemical reactions in which carbon and microalloying additives can participate, the Gibbs free energy was determined in accordance with formulas given in [21]. It has been established that within 1300 to 4000°C, carbon monoxide does not enter into chemical interaction with the main alloying elements — silicon, manganese, vanadium, and copper. The course of reduction reactions, as well as the formation of vanadium carbides is possible. Researches in this direction will be continued.

6. Conclusions
It has been established that welding at negative temperatures of A500S vanadium microalloyed reinforcing steel can lead to the formation of quenching structures and cracks in the welded joint.

The use of unregulated heating of the reinforcing bars with a gas flame causes the steel to soften due to elimination of the effect of thermo-mechanical hardening, as well as cause a decrease in metal viscosity.

The use of mechanized arc welding in a reductive carbon monoxide atmosphere ensures the absence of quenching structures, a decrease in the hardness of the weld metal, as well as the required strength properties of the welded joint.

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