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Assessment of the possibility of resistance butt welding of pipes made of heat-resistant steel *0.15C-5Cr-Mo*

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ABSTRACT

Introduction. Cr-Mo steels are used in high-temperature and high-pressure applications, including critical components of modern supercritical and ultra-supercritical thermal power plants. Due to its unique ability to withstand high temperatures and pressures, these steels are also used in critical components of fast breeder nuclear reactors. The heterogeneity of the microstructure and mechanical properties throughout the welded joint is a decisive factor leading to a decrease in its performance and premature failure. Post-weld heat treatment is the main method for improving mechanical properties. However, the mechanism for the evolution of mechanical properties associated with heterogeneous microstructure after heat treatment remains unclear, which complicates the design of the heat treatment process and a comprehensive assessment of its effect. **The purpose of the work** is to assess the possibility of the resistance butt welding method of welding pipes made of *0.15C-5Cr-Mo* steel, to select technological parameters for resistance butt welding of pipes to obtain high mechanical properties. **Research methods.** The experiments were carried out on a resistance butt welding machine *MSO-201N*. Mechanical tests for static tension, chemical composition analysis and metallographic studies were carried out. **Results and discussion.** Technological parameters of resistance butt welding of pipes, changed in the course of our research, show that upsetting pressure and spark allowance affect the final strength properties of the welded joint. Based on the results of metallographic studies, the following features of the evolution of the microstructure can be noted. A noticeable decrease in the content of primary coarsened ferrite is observed in the structure of the weld after tempering. The use of post-weld heat treatment made it possible to reduce the hardness in the welded joint to the level of regulatory requirements. **Results presented.** The effect of heat treatment on mechanical properties is analyzed based on a comparison of heat treatment modes: stress relief annealing and normalization + tempering in terms of improving mechanical properties during tensile tests. The results show that after tempering, the evolution of mechanical properties in each sub-zone of the welded joint is sequential, i.e., hardness and tensile strength decrease and toughness increases. It is noteworthy that the most significant increase in toughness is observed in the weld zone, primarily due to a significant decrease in the presence of hypoeutectoid ferrite.

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Introduction

Operation of power plants at elevated temperature and pressure requires materials with high long-term strength, high thermal conductivity and high corrosion resistance [1–8]. Numerous important components of thermal power plants, such as steam lines, boilers, heat exchangers, etc., operate at elevated temperatures and high pressures. Therefore, these components should be resistant to creep and corrosion throughout its 30–40 year service life. Over the past half century, the operating temperature of the steam in the

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boiler has increased from 450 °C to 568 °C, and the pressure has increased approximately six times to 25 MPa, which increases the boiler efficiency. The equipment used to manufacture the boiler consists of a manifold and pipes of various designs. Components such as pressure vessels require low water and steam temperatures. Pressure vessels are mainly exposed to steam and water from the boiler, as well as flue gases from economizers, furnace walls, preheaters and superheaters. The components are mainly made from small diameter steel tubes.

Increasing the thermal efficiency of power plants by increasing the operating temperature and pressure of steam entering the turbine has led to the development of a new category of heat-resistant steels. The most commonly used materials in power plants operating at high temperatures and high pressures are ferritic/martensitic steel with improved creep resistance, nickel-based superalloys and austenitic stainless steel [1–5]. Potential candidate materials for ultra-supercritical power plants are *Ni*-based alloys such as *Inconel 617*, *Inconel* 625 and *Inconel* 740 [3, 4]. These *Ni*-based alloys have excellent corrosion resistance, good oxidation resistance and high creep strength at 650 °C. However, since *Ni*, *Cr* and *Mo* are the key alloying elements in these alloys, these *Ni*-based alloys are expensive [5–9]. In addition, these alloys are technically difficult to manufacture.

In the mid-1960s, 12 % *CrMoV* steels were developed for thin- and thick-walled power plant components. The operating temperature of such components was 565 °C. The creep strength of 12 % *CrMoV* steels was achieved by solid solution strengthening and precipitation strengthening. Modern boilers use chromium-molybdenum steels *5Cr-1Mo*, *9Cr-1Mo*, modified *9Cr-1Mo* steels with *Nb*, *V*, *W* or *12Cr*, which have better thermal and mechanical properties compared to 300 series austenitic stainless steels.

Domestic analogues are steel *0.15C-5Cr-Mo* and its modifications *0.15C-5Cr-Mo-V* and *12C-8Cr-W-V* [10, 11]. Chromium (*Cr*), tungsten (*W*) and molybdenum (*Mo*) are the main alloying elements present in steel and provide better creep resistance at elevated temperature and pressure. The strength of chromium-molybdenum steels is due to its high dislocation density. Materials soften as dislocation density decreases, for example, when dislocations move, meet, and annihilate each other. Steels with a *Cr* content of 2–13 % maintain dislocation density at high temperatures and, therefore, strength, since the microstructure slows down the movement of dislocations. It is difficult for dislocations to cross grain boundaries, and carbides and precipitates along grain boundaries are relatively immobile and cause dislocation pinning, as shown in [2–5].

Creep is a thermally activated process. It is defined as the slow unsteady deformation of a material under the influence of a constant load. The high operating temperature and pressure requirements of such a modern power plant are leading to the development of creep strength enhanced ferritic (*CSEF*) and martensitic steels. For nuclear and thermal power plants, creep strength enhanced ferritic (*CSEF*) steels are considered to be a better material than austenitic stainless steel due to its low coefficient of thermal expansion, good thermal conductivity and high creep strength. Creep occurs due to prolonged exposure of the material to a constant applied stress below yield strength of the material. It is necessary to know the mechanical properties of steel, including reduction in *Young's* modulus, yield strength, and reduction in tensile strength at various stress levels and elevated temperatures. To reveal mechanical properties at elevated temperatures, stress-strain relationships should be established. Currently, both steady state and transient state tests are used to measure the mechanical properties at high temperatures. In this case, temperature-dependent physical mechanisms, such as volume diffusion, glide and climb dislocations, are a response to creep phenomena in a crystalline material.

Fusion welding (manual arc welding, gas-shielded welding, submerged welding) is a commonly used welding process for steel *0.15C-5Cr-Mo* and its modifications *0.15C-5Cr-Mo-V* and *0.15C-5Cr-V-W*, which includes intense heat input and its dissipation into the base metal due to thermal conductivity [6–9]. Preheating when welding heat-resistant steels prone to hardening helps ensure the quality of the weld and reduces the likelihood of cracking. Before welding steel pipes or plates up to 20 mm thick or more in workshops or on-site, preheating to 300-450°C is commonly used [11–18]. The welding process is usually followed by induction heat treatment to replace the coarse microstructure associated with high heat input during the joining operation with finer pre-austenite grains and fine ferrite phases.

This is due to the fact that the microstructure adjacent to the fusion zone is transformed into hard phases such as martensite and bainite during rapid cooling. These hard phases result in low impact toughness and high hardness values of the material due to the content of a significant amount of residual stresses. Thus, pipe welds require an additional cycle of post-weld heat treatment to restore mechanical properties and reduce the likelihood of brittle failure in the joint area. The most widely used post-weld treatment mode is the normalization cycle. Normalizing treatment can significantly improve weld alignment characteristics; however, process parameters include maximum heating temperature, heating rate, holding time, and initial cooling water temperature. In addition to normalizing treatment, secondary normalization, quenching, quenching and tempering, and other thermomechanical treatments are carried out to increase the impact toughness of the pipeline [4, 12–19].

Although welding of high chromium steels has become a well-known method that is widely used in the conventional power industry, the weld characteristics of high *Cr* and *Cr-Mo* steels are still often considered a life-limiting factor at high temperatures. In fact, a high percentage of failures in the power generation industry have been reported to be welding-related [4–9]. Moreover, despite extensive experience in welding high chromium steels, many certified welding procedures have been developed for specific applications, and the environmental conditions of new applications can greatly affect the weld.

In [19], an analysis was carried out based on world experience of failures due to incorrect heat treatment of heat-resistant steels after welding. It is concluded that the creep damage and observed cracking mechanisms resulted from the high degree of mechanical stress experienced by the failed pipe in the heat affected zone (*HAZ*) immediately adjacent to the pipe weld [20].

One solution to this problem is to develop a new material whose microstructure in the *HAZ* would be similar to the microstructure of the base metal. This was achieved, for example, by adding boron [5–7]. Several effects are used to achieve good quality welded joints: optimization of the welding procedure and parameters, development of a suitable filler metal and the use of post-weld heat treatment. Currently, research is being conducted to develop new welding processes (laser, electron beam, friction welding) to improve the characteristics of *0.15C-5Cr-Mo* and its modifications *0.15C-5Cr-Mo-V* and *0.15C-5Cr-V-W* steels is a promising direction [6–9, 12–33].

For example [22], Magnetically Impelled Arc Butt (*MIAB*) welding is a joining method that replaces traditional welding methods such as resistance welding, friction welding, flash welding and butt welding. This is a solid-state process in which a rotating arc heats the ends of the tubes, followed by a forging process to complete the joining of the workpieces. Magnetic-flux density and current interact to create a *Lorentz* force that causes the arc to move along the adjoining surfaces. This process has been found to provide high tensile strength and defect-free welds in ferrous materials, and for this reason it is predominantly used in the automotive industry for joining metal pipes. Additionally, this joining procedure can be used in the manufacture of boilers, heat exchangers, furnace piping in the petrochemical industry, and in the manufacture of other safety-critical high-pressure machine parts. Using Magnetically Impelled Arc Butt welding (*MIAB*), it is possible to connect pipes with an outer diameter from 75 mm to 450 mm and a wall thickness of up to 10–35 mm in 10–15 s [22].

However, as many researchers believe [1, 5, 8, 9, 15], power plant workers may be slow to adopt new materials and new welding methods for a number of reasons, including the development of new industry sector codes and standards [11], as well as confidence in long-term work of already assembled welded units in machines and mechanisms.

At the same time, the well-known method of resistance butt welding of pipes is widely used in boiler making, pipeline construction, and the production of oil equipment. Depending on the cross-section and material of the pipe, continuous or flash welding with preheating is selected.

This paper presents the results of research on resistance butt welding of pipes made of *0.15C-5Cr-Mo* steel. ***The purpose of the work*** is to assess the possibility of the resistance butt welding method of welding pipes made of *0.15C-5Cr-Mo* steel, to select technological parameters for resistance butt welding of pipes to obtain high mechanical properties.

Materials and methods

The base material used in this study was a seamless pipe with an outer diameter of 25 mm and a wall thickness of 2.5 mm. The pipe material was steel *0.15C-5Cr-Mo* (Table 1), delivered in a normalized and tempered state in accordance with *GOST 550-75*. When analyzing the chemical composition of pipe materials, the following measuring instruments and testing equipment were used: X-ray spectrometer *SRM-25*, express carbon analyzer *AN-7529*. Mechanical properties of as delivered material are presented in Table 2. To determine the mechanical properties of a pipe steel, 3 samples were taken in accordance with industry standards [11].

For welding, a resistance butt welding machine *MSO-201N* was used, the welding current was 7,400–8,000 A. The process of resistance welding of pipes is shown in Fig. 1.

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Table 1

Chemical composition of pipes for welding

Steel grade	Elemental content, %							
	C	*Si*	*Mn*	*Cr*	*Mo*	*Ni*	*S*	*P*
0.15C-5Cr-Mo According to *GOST 20072-74*	< 0.15	< 0.5	< 0.5	4.5–6.0	0.45–0.60	<< 0.6	< 0.025	< 0.030
In fact	0.1	0.35	0.22	5.51	0.52	0.35	0.012	0.012

Table 2

Mechanical properties of *0.15C-5Cr-Mo* steel pipe

Assortment	Yield strength, $\sigma_{0.2}$, MPa, min	Ultimate strength, σ_u, MPa, min	Percentage elongation, δ_5, %, min	Percentage reduction of area, ψ, %, min	Hardness, HB, max
Pipe according to *GOST 550-75*	216	421	22	50	170
In fact	220	450	25	54	128

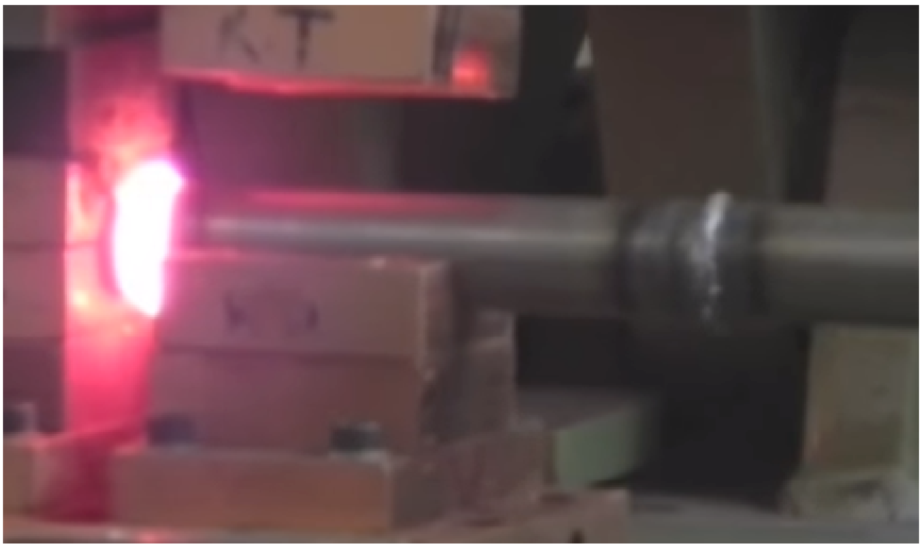

Fig. 1. Pipe welding on the *MCO-201H* machine

welding and after additional heat treatment. Heat treatment modes for welded pipe specimens were: normalization at 950–1,000 °C, tempering at 780–800 °C. Heat treatment was carried out on an induction installation *MGZ-102* with a current frequency of 2,500 Hz, in a ring split single-turn inductor with an internal diameter of 40 mm and a width of 30 mm. The tempering modes (temperature 500–600 °C) were selected experimentally by changing the current in the range of 25–30 A and adjusting the generator excitation voltage 180–200 V, while the power was 5–6 kW. And in the normalization mode (850–1,000 °C), the current was in the range of 50–60 A, the generator excitation voltage was 350–370 V, and the power was 17.5–22.2 kW. The effect of welding parameters on the thermal cycles of the weld, the microstructure and mechanical properties of the joints was studied by changing the upsetting pressure, upsetting allowance and upsetting current time, under the condition that the main parameters were constant. The performance and failure behavior of various welded pipes were estimated by conducting mechanical tensile tests on an *Instron* electromechanical testing machine with a lifting capacity of 1,000 kN. Hardness according to the *GOST* requirements for heat-resistant steels was determined on a *Brinell* hardness tester *ITB-3000-III-AZhP*. The welded specimens were subjected to the flattening and bend tests, which are a quality control tests to evaluate the ductility and integrity of the butt weld joint. The microstructures were determined using an *MET-2* optical microscope, a *JEOL JIB-4501* scanning electron microscope equipped with an energy dispersive spectroscopy (*EDS*) spectrometer, model *Bruker X/Flash 6/60*, and an *X* spectrometer, and also equipped with an electron backscatter diffraction detector (*EBSD*). The obtained data was analyzed using *HKL Channel 5* software.

Results and discussion

The base metal (Fig. 2) contains ferrite and granular carbides in the form of inclusions up to 1 μm in size uniformly distributed over the entire area of the section. It is known that part of the molybdenum is in ferrite, and chromium and carbon are in carbides; this fact provides the heat resistance of the steel [1–5]. It was observed that the base material consists mainly of α-ferrite grains with some Fe_3C distributed around it. The heat-affected zone (*HAZ*) was the region where the elevated temperature was high enough (but below the melting point) to change the microstructure. During welding, the base material was transformed into smaller equiaxed grains in the *HAZ* due to the elevated temperature. New grains nucleated and grew at grain boundaries. However, the short duration of the welding process limited grain growth.

In welded pipes without heat treatment in the weld joint zone at a distance of 7 mm in both directions, the main structure of the sorbite, there are separate areas of acicular bainite (Fig. 3). As expected, the grain size near the fusion line was significantly larger than at a distance. The peculiarity of bainitic ferrite was that the ferrite grew from the grain boundary of the preceding austenite to the inner grain and formed parallel laths. Bainitic ferrite arose as a result of a mixture of shear and diffusion transformations at high cooling rates. The hardness of the metal is 295–321 HB.

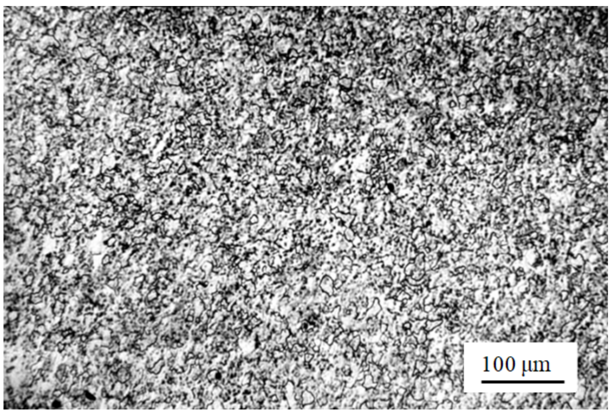

Fig. 2. Base metal microstructure

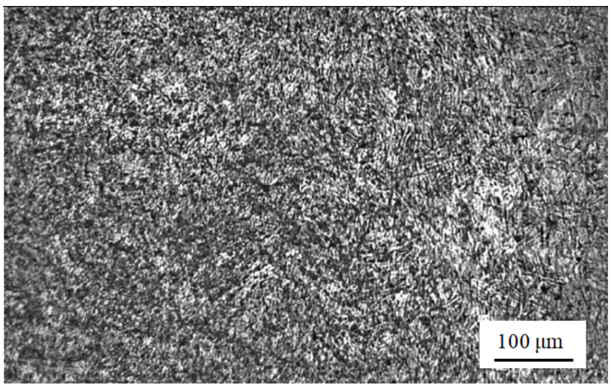

Fig. 3. Microstructure of welded pipe metal in the joint zone at a distance of 7 mm

In the transition zone to the base metal at a distance of 10–12 mm, the structure is sorbite and ferrite (Fig. 4). The microstructure is represented by equiaxed fine-grained grains due to dynamic recrystallization. At the same time, the size of the ferrite grain compared to the base metal has decreased from 25 μm to approximately 4 μm, and the hardness decreases to 180–235 HB. As we move (when examined on an optical microscope) along the *HAZ* to the base metal, the structure of sorbite and ferrite smoothly transforms into the structure of the base metal ferrite + granular carbides (Fig. 2).

After local heat treatment of the weld in the tempering mode, a structure of ferrite + sorbite is formed along the fusion line (Fig. 5). The length of this zone is 0.5 mm. The hardness in this zone is 134–150 HB.

After local heat treatment of the welded joint in the normalization + tempering mode, the structures in the joint zone (Fig. 6) and the *HAZ* at the distance of 15 mm from the axis consists of sorbite and a ferrite field, with a hardness in this zone of 207–212 HB. In this area, a decrease in hardness values occurs due to the presence of ferrite.

Fig. 7 shows the distribution of hardness over the welded joint after welding, after welding and tempering, after welding and complex heat treatment normalization + tempering. It can be seen that heat treatment of the welded joint significantly reduces the hardness.

Fig. 8 visually shows the results of flattening and bending of welded specimens. Both the welded material and the base material specimen passed the bending test without visible defects or cracks. The bend angle of the pipes in the initial state and after local heat treatment according to the tempering mode was 180°. At the same time, after complex heat treatment normalization + tempering, the bend angle decreased and amounted to only 45–70°.

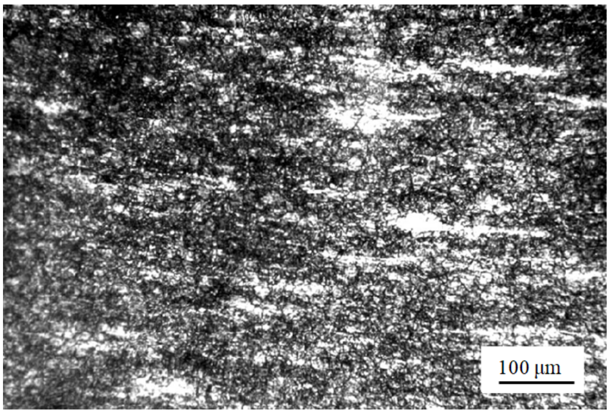

Fig. 4. Microstructure of metal in the transition zone to the base one

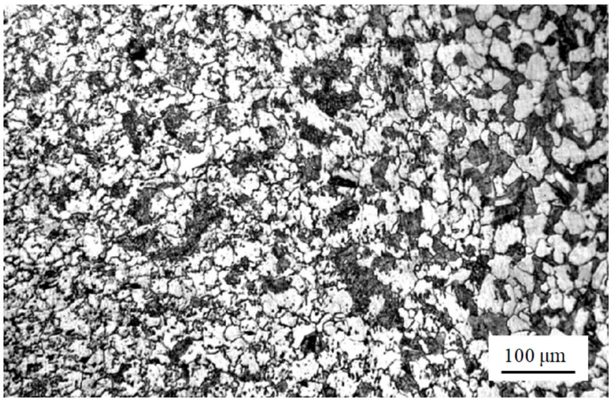

Fig. 5. Microstructure of metal in the joint area after tempering

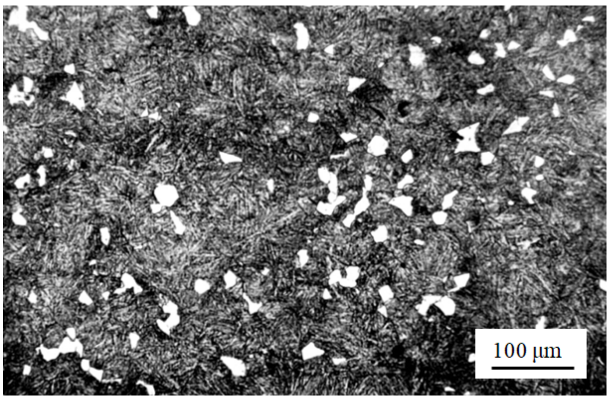

Fig. 6. Microstructure of metal in *HAZ* after normalization and tempering

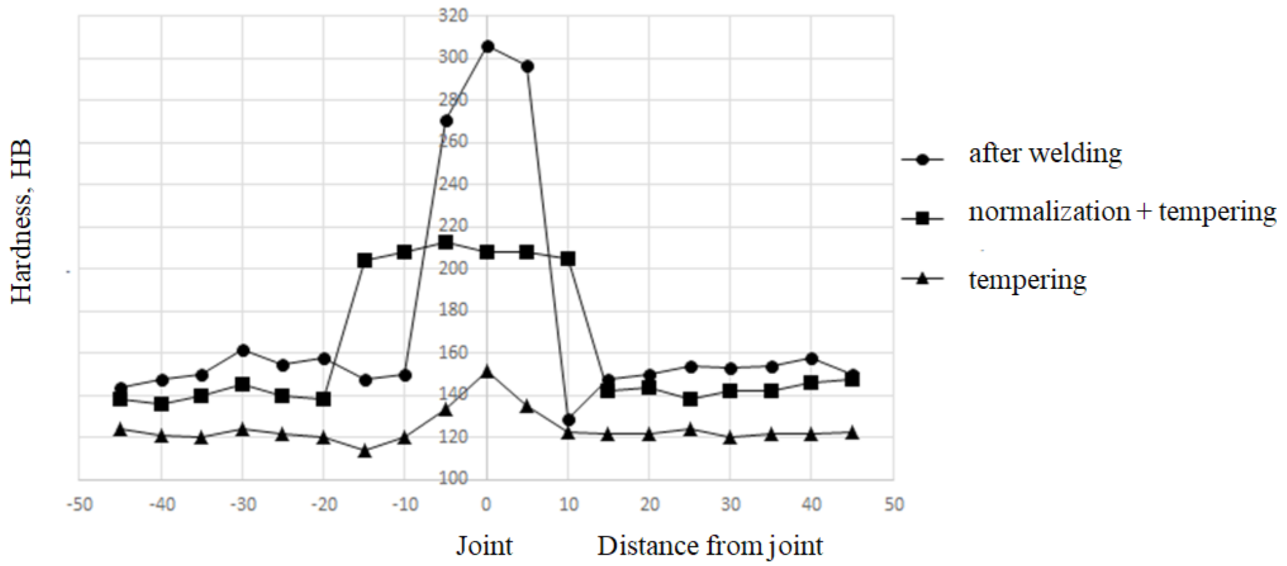

Fig. 7. Hardness distribution in the welded joint after various treatment modes

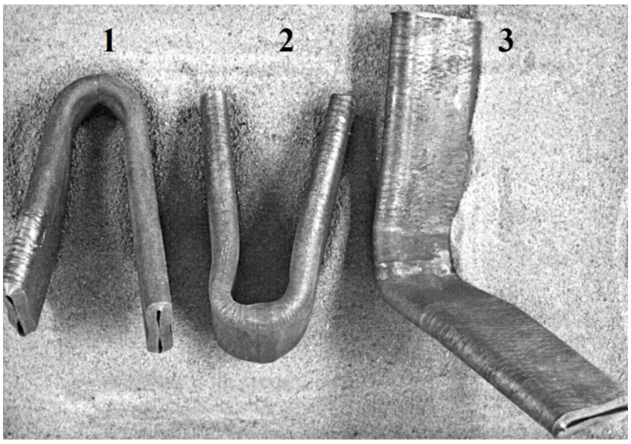

Fig. 8. Welded pipe joints after flattening + bending test:

1 – original pipe; ***2*** – welded pipe in condition after tempering; ***3*** – welded pipe in condition after complex heat treatment normalization + tempering

The ultimate strength of welded joints made with different welding parameters is shown in Table 3 based on the test results of three specimens in each series. According to the test results, the ultimate strength of joints made from *0.15C-5Cr-Mo* steel is within 400–470 MPa, which is significantly higher than the base metal. During tensile tests, the destruction of the metal of a pipe made of steel *0.15C-5Cr-Mo* occurred at a distance of 60–70 mm from the joint.

Results and discussion

Technological parameters of resistance butt welding of pipes, changed in the course of our research, show that upsetting pressure and sparking allowance affect the final strength properties of the welded joint (Table 3). Resistance butt welding is a two-stage electric resistance welding process. In the initial stage of welding, the two parts to be welded are fully heated to obtain adequate plastic deformation capability. In the upsetting stage, after the flashing process is completed, sufficient upset force is applied to the joint

Table 3

Ultimate strength of *0.15C-5Cr-Mo* steel welded joints made with different welding parameters

Series no.	1	2	3
Sparking allowance, mm	12	6	12
Upsetting pressure, MPa	120	120	140
Upsetting allowance, mm	18	18	18
Upsetting current time, s	5	5	5
Ultimate strength, MPa, average of three specimens	398	405	470

to close the gap between the adjoining surfaces and remove the liquid metal and oxide inclusions. The upsetting stage occurs when the two ends are brought closer together under the influence of an axial force at a controlled speed. Meanwhile, a certain plastic deformation occurs in the joint, resulting in dynamic recrystallization and recrystallization during the upsetting process to form a strong joint. Welding thermal cycles have high peak temperatures and high heating and cooling rates. As the spark allowance increases from 6 mm to 12 mm, the heating rate (peak temperature/heating time) decreases. During flash heating, the greater the flash allowance, the longer it takes to reach peak temperature, resulting in a slower heating rate. During the cooling process, the time $t_{8/5}$ increases from 26.0 s to 32.5 s, since the upsetting allowance increases from 12 mm to 16 mm, which can be explained by an increase in heat input during welding.

In resistance butt welding, the interface of both pipe specimens was heated to the melting temperature, most of the resulting liquid metal splashed out from the interface, and the remaining liquid metal formed very fine grains. Peak temperatures in the *HAZ* were in the solidus-liquidus range, so its width was also limited. Depending on the peak temperatures and microstructural characteristics, the heated pipe specimens can be divided into four zones: 1) molten zone, 2) semi-molten zone, 3) coarse-grained zone, and 4) fine-grained zone. Based on the results of metallographic studies, the following features of the evolution of the microstructure can be noted. A noticeable decrease in the content of primary coarsened ferrite is observed in the structure of the weld after tempering heat treatment. It should be noted that blocky primary coarsened ferrite along grain boundaries is always considered as the main factor contributing to the rapid propagation of cracks and a decrease in impact toughness. Therefore, it can be assumed that the overall performance of the weld can be significantly improved. In the coarse-grained heat-affected zone on the right side of the fusion line, a portion of the bainite undergoes decomposition and the characteristic lamellar structure of the ferrite becomes less distinct, resulting in a more uniform microstructure distribution. After heat treatment (tempering) of the welded joint, the grain size in the fine-grained zone increases due to the decomposition of part of the pearlite, and the ferrite increases in size (Fig. 6). In the base metal zone, there is no significant change in grain size, but the pearlite content is noticeably reduced.

When analyzing the results of Fig. 7, it was found that the distribution of microhardness over the welded joints in the post-weld heat treatment modes of "tempering" and "normalization + tempering", annealing and tempering heat treatment is significantly reduced. The general trend in the sizes of the *HAZ* areas is as follows: the weld area is larger than the heat-affected zone, which is larger than the base material zone. This difference in hardness across the weld joint and *HAZ* as a whole is reflected in variations in the content of elements, microstructure, and grain size in different microzones of the welded joint. More precisely, the weld zone has the highest microhardness due to the higher content of elements such as *Mn* and *Si*, which play an important role in solid solution strengthening. In addition, the microstructure of the weld zone consists predominantly of bainite and ferrite, which also determines the highest microhardness. During resistance butt welding, the heat-affected zone above 1,300 °C (*WZ*) experienced a thermal cycle with a higher peak temperature and greater plastic deformation caused by dislocation motion, resulting in dynamic recrystallization and recrystallization in this zone. It is known that the plastic deformation experienced in the weld joint zone tended to increase the number of dislocations, while the number of dislocations tended to decrease during dynamic recrystallization and recrystallization process. The heat-affected zone has a microstructure similar to that of the base metal, but has relatively smaller grain sizes, resulting in higher hardness values. In addition, after heat treatment in the tempering mode, a significant decrease in microhardness occurs throughout the welded joint. The difference in hardness between different zones is reduced, especially between the heat-affected zone and the base metal zone. In combination with the observation of the microstructure, it is assumed that the decrease in hardness occurs mainly due to the partial decomposition of bainite and pearlite, the growth of ferrite regions (Fig. 6) with lower hardness and due to the formation of tempered structures.

Analysis of the stress-strain curves during testing of pipe specimens showed that the final destruction occurred in the zone of the base material of the specimens both under heat treatment conditions in the normalization + tempering mode, and under the conditions of the tempering mode. There can be two reasons: firstly, the content of alloying elements in weld joint is higher than in the base metal (as shown in Table 3), which indicates that the high strength of the weld obtained during welding compared to the base metal corresponds to the strength of the base metal of the pipes. Secondly, the coarse-grained region in the heat-affected zone experiences strengthening of the alloy due to the diffusion of elements from the weld metal, while the fine-grained zone, characterized by small and evenly distributed grain sizes, promotes strengthening in the heat-affected zone. As a result, the overall strength of the heat-affected zone is higher than that of the base metal.

Research has shown that the resistance butt welding process forms quenching structures of the acicular bainite type, with a hardness of 380 HB in the weld joint and *HAZ*, increasing strength but limiting ductility, as shown by tensile tests and optical microscopic analysis. Hardness measurements clearly confirm these results, showing an increase in hardness in the weld joint and *HAZ* zone of the specimens. However, as for the bending tests, no cracks were recorded, but the high hardness of the weld moves the bending center from the weld to the base material.

The hardness values of the specimens after welding increased slightly due to the formation of bainite in the *HAZ*. Rapid cooling in the *HAZ* where the temperature (during welding) was above ***Ac3*** can promote the formation of hard phases such as martensite and bainite in the weld joint. The hardness values after welding were 310 HB. This was due to the fact that the microstructure, completely converted to lath, had a high dislocation density. However, since bainite predominated, virtually no lath martensite was observed. During the normalization process, grain recovery and growth occurred, while the hardness values decreased compared to the hardness of the sample after welding (Fig. 7). After tempering, the hardness values were approximately 130–150 HB lower compared to the hardness values of the specimen after welding. Fig. 7 shows the hardness changes that occur in the fusion zone and *HAZ* during tempering and normalization + tempering. When the tempering temperature was increased to 600 °C the hardness decreased, but with a further increase in temperature it remained stable. Therefore, it can be understood that 600 °C may be the best tempering temperature in terms of hardness.

Thus, it is obvious that after resistance butt welding of pipes made of *0.15C-5Cr-Mo* steel, the bainite-type structures formed in the *HAZ* increase the strength properties of the welded joint and the hardness, which requires additional heat treatment of the joint. It is worth noting that no cold cracking effect was felt in the specimens due to the waiting time between the welding process and subsequent heat treatment. In this work, the effect of post-weld heat treatment on the microstructure and mechanical properties of various *0.15C-5Cr-Mo* pipe welded joints was investigated. In further research, we plan to develop a practical technology with optimal welding and heat treatment conditions for the purpose of implementing it in real production.

Conclusion

1. It is established that pipes made of 0.15C-5Cr-Mo steel with a size of 25×2.5 mm during resistance butt welding have satisfactory weldability due to the formation of bainitic structures of increased hardness in the joint zone. Taking into account the thermophysical properties of the pipe material, resistance butt welding should be carried out under hard modes with maximum upsetting pressure.

2. It is shown that hardness is an important indicator reflecting changes in the microstructure in the welded joint. Changes in strength show a positive correlation with changes in hardness, while changes in ductility show a negative correlation with changes in hardness. Thus, hardness testing can be used in engineering applications to evaluate the effectiveness of post-weld heat treatment in improving the properties of a welded joint.

3. To obtain the required mechanical properties of welded joints of pipes made of steel 0.15C-5Cr-Mo welded by resistance butt welding, it is necessary to carry out local heat treatment according to tempering modes or normalization with tempering.

References

1. Wen J.-b., Zhou C.-Y., Li X., Pan X.-M., Chang L., Zhang G.-D., Xue F., Zhao Y.-F. Effect of temperature range on thermal-mechanical fatigue properties of P92 steel and fatigue life prediction with a new cyclic softening model. *International Journal of Fatigue*, 2019, vol. 129, p. 105226. DOI: 10.1016/j.ijfatigue.2019.105226.

2. Seo W., Suh J., Shim J.H., Lee H.S., Yoo K.B., Choi S. Effect of post-weld heat treatment on the microstructure and hardness of P92 steel in IN740H/P92 dissimilar weld joints. *Materials Characterization*, 2020, vol. 160, p. 110083. DOI: 10.1016/j.matchar.2019.110083.

3. Kumar A., Pandey C. Some studies on dissimilar welds joint P92 steel and Inconel 617 alloy for AUSC power plant application. *International Journal of Pressure Vessels and Piping*, 2022, vol. 198, p. 104678. DOI: 10.1016/j.ijpvp.2022.104678.

4. Dak G., Pandey C. A critical review on dissimilar welds joint between martensitic and austenitic steel for power plant application. *Journal of Manufacturing Processes*, 2020, vol. 58, pp. 377–406. DOI: 10.1016/j.jmapro.2020.08.019.

5. Masuyama F. Low-alloyed steel grades for boilers in ultra-supercritical power plants. *Materials for ultra-supercritical and advanced ultra-supercritical power plants.* Woodhead Publ., 2017, pp. 53–76. DOI: 10.1016/B978-0-08-100552-1.00002-6.

6. Gabrel J., Bendick W., Vandenberghe B., Lefebvre B. Status of development of VM 12 steel for tubular applications in advanced power plants. *Energy Materials*, 2006, vol. 1 (4), pp. 218–222. DOI: 10.1179/174892406X173657.

7. Shigeyama H., Takahashi Y., Siefert J., Parker J. Creep-fatigue life evaluation for grade 91 steels with various origins and service histories. *Metals*, 2024, vol. 14 (2), p. 148. DOI: 10.3390/met14020148.

8. Halimov A.A., Gharinova N.V., Khalimov A.G., Fairushin A.M. Obespechenie tekhnologicheskoi prochnosti svarnykh soedinenii iz martensitnykh khromistykh stalei tipa 15Kh5M [Ensuring technological strength of welding joints of chromium martensitic steel 15CR5M]. *Neftegazovoe delo = Oil and Gas Business*, 2012, vol. 10, no. 3, pp. 102–108. (In Russian).

9. Khalimov A.A., Zharinova N.V. Optimizatsiya tekhnologii vysokotemperaturnoi termicheskoi obrabotki svarnykh soedinenii iz khromistykh zharoprochnykh stalei [*High-temperature thermal process technology optimization of the welded joints from chromium heat-resistant steels*]. *Tekhnologiya Mashinostroenya = Technology of Mechanical Engineering*, 2009, no. 10, pp. 19–25.

10. GOST 20072–74. *Stal' teploustoichivaya. Tekhnicheskie usloviya* [State Standard 20072–74. Heat-resistant steel. Specifications]. Moscow, Standards Publ., 1974. 19 p.

11. RD 153-34.1-003-01. *Svarka, termoobrabotka i kontrol' trubnykh sistem kotlov i truboprovodov pri montazhe i remonte energeticheskogo oborudovaniya (RTM-1s)* [Regulating document 153-34.1-003-01. Welding, heat treatment and control of pipe systems of boilers and pipelines during installation and repair of power equipment (RTM-1s)]. Approved by the order of the Ministry of Energy of Russia from 02.07.2001. St. Petersburg, DEAN Publ., 2002. 463 p.

12. Iskhakov A.R., Medvedev Yu.S., Korolev N.M., Zainullin R.S., Khalimov A.G., Kutluev I.M., Chernykh Yu.A., Tishkin A.F *Poluavtomaticheskaya svarka v srede uglekislogo gaza stali tipa 15Kh5M (vremennaya instruktsiya)* [Semi-automatic welding in a carbon dioxide environment for steel type 15X5M (temporary instructions)]. Moscow, TSINTIkhimneftemash Publ., 1992. 8 p.

13. *Ruchnaya elektrodugovaya svarka s regulirovaniem termicheskikh tsiklov konstruktivnykh elementov neftekhimicheskogo oborudovaniya iz zakalivayushchikhsya stalei tipa 15Kh5M* [Manual electric arc welding with regulation of thermal cycles of structural elements of petrochemical equipment made of hardening steels of type 15X5M]. PTM 26-17-076-87. Moscow, Minkhimmash Publ., 1987. 26 p. (In Russian).

14. Tukaev R.F., Fairushin A.M., Kuchukov T.M. Sovershenstvovanie tekhnologii izgotovleniya uzla «truba – trubnaya reshetka» kozhukhotrubchatogo teploobmennogo apparata iz zharoprochnoi stali 15Kh5M primeneniem lazernoi svarki [Improving the manufacturing technology of the "pipe – tube sheet" assembly of a shell-and-tube heat exchanger made of heat-resistant steel 15X5M using laser welding]. *Sovremennoe mashinostroenie. Nauka i obrazovanie = Modern mechanical engineering. Science and education*, 2013, no. 3, pp. 1179–1185. (In Russian).

15. Tokarev A.S., Karetnikov D.V., Rizvanov R.G., Cherepashkin S.E., Mulikov D.Sh. Otsenka korrozionnoi stoikosti kombinirovannykh soedinenii trub s trubnoi reshetkoi, poluchennykh s primeneniem razlichnykh sposobov svarki [Assessment of the corrosion resistance of combined pipe-tube sheet joints obtained using various welding methods]. *Neftegazovoe delo = Oil and Gas Business*, 2019, no. 6, pp. 114–133. DOI: 10.17122/ogbus-2019-6-114-133. (In Russian).

16. Shtayger M.G., Balanovskiy A.E., Kargapoltsev S.K., Gozbenko V.E., Karlina A.I., Karlina Yu.I., Govorkov A.S., Kuznetsov B.O. Investigation of macro and micro structures of compounds of high-strength rails implemented by contact butt welding using burning-off. *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 560 (1), p. 012190. DOI: 10.1088/1757-899X/560/1/012190.

17. Balanovskiy A.E., Shtayger M.G., Karlina A.I., Kargapoltsev S.K., Gozbenko V.E., Karlina Yu.I., Govorkov A.S., Kuznetsov B.O. Surface hardening of structural steel by cathode spot of welding arc. *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 560 (1), p. 012138. DOI: 10.1088/1757-899X/560/1/012138.

18. Balanovskiy A.E., Astafyeva N.A., Kondratyev V.V., Karlina Yu.I. Study of impact strength of C-Mn-Si composition metal after wire-arc additive manufacturing (WAAM). *CIS Iron and Steel Review,* 2022, vol. 24, pp. 67–73. DOI: 10.17580/cisisr.2022.02.10.

19. Balanovskiy A.E., Karlina A.I., Kolosov A.D., Karlina Y.I. Study of the effect of nanomodifiers from silicon production wastes on morphological form of gray cast iron graphites. *CIS Iron and Steel Review*, 2021, vol. 21, pp. 64–69. DOI: 10.17580/cisisr.2021.01.11.

20. Fabricius A., Jackson P.S. Premature grade 91 failures – worldwide plant operational experiences. *Engineering Failure Analysis*, 2016, vol. 66, pp. 398–406.

21. Liu Z., Hu X., Yang Z., Yang B., Chen J., Luo Y., Song M. Optimization study of post-weld heat treatment for 12Cr1MoV pipe welded joint. *Metals*, 2021, vol. 11 (1), p. 127. DOI: 10.3390/met11010127.

22. Silwal B., Li L., Deceuster A., Griffiths B. Effect of post-weld heat treatment on the toughness of heat-affected zone for grade 91 steel. *Welding Journal*, 2013, vol. 92 (3), pp. 80s–87s.

23. Chaturvedi M., Vendan Subbiah A., Simion G., Rusu C.C., Scutelnicu E. Critical review on magnetically impelled arc butt welding: challenges, perspectives and industrial applications. *Materials*, 2023, vol. 16, p. 7054. DOI: 10.3390/ma16217054.

24. Skeeba V.Yu., Ivancivsky V.V., Kutyshkin A.V., Parts K.A. Hybrid processing: the impact of mechanical and surface thermal treatment integration onto the machine parts quality. *IOP Conference Series: Materials Science and Engineering*, 2016, vol. 126 (1), p. 012016. DOI: 10.1088/1757-899x/126/1/012016.

25. Efremenkov E.A., Martyushev N.V., Skeeba V.Yu., Grechneva M.V., Olisov A.V., Ens A.D. Research on the possibility of lowering the manufacturing accuracy of cycloid transmission wheels with intermediate rolling elements and a free cage. *Applied Sciences*, 2022, vol. 12 (1), p. 5. DOI: 10.3390/app12010005.

26. Martyushev N.V., Skeeba V.Yu. The method of quantitative automatic metallographic analysis. *Journal of Physics: Conference Series*, 2017, vol. 803 (1), p. 012094. DOI: 10.1088/1742-6596/803/1/012094.

27. Skeeba V.Yu., Ivancivsky V.V. Reliability of quality forecast for hybrid metal-working machinery. *IOP Conference Series: Earth and Environmental Science*, 2018, vol. 194 (2), p. 022037. DOI: 10.1088/1755-1315/194/2/022037.

28. Zverev E.A., Skeeba V.Y., Skeeba P.Y., Khlebova I.V. Defining efficient modes range for plasma spraying coatings. *IOP Conference Series: Earth and Environmental Science*, 2017, vol. 87 (8), p. 082061. DOI: 10.1088/1755-1315/87/8/082061.

29. Skeeba V.Yu. Hybrid process equipment: improving the efficiency of the integrated metalworking machines initial designing. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 2, pp. 62–83. DOI: 10.17212/1994-6309-2019-21.2-62-83. (In Russian).

30. Borisov M.A., Lobanov D.V., Yanyushkin A.S., Skeeba V.Yu. Investigation of the process of automatic control of current polarity reversal in the conditions of hybrid technology of electrochemical processing of corrosion-resistant steels. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 1, pp. 6–15. DOI: 10.17212/1994-6309- 2020-22.1-6-15. (In Russian).

31. Mamadaliev R.A., Bakhmatov P.V., Martyushev N.V., Skeeba V.Y., Karlina A.I. Influence of welding regimes on structure and properties of steel 12KH18N10T weld metal in different spatial positions. *Metallurgist*, 2022, vol. 65 (11–12), pp. 1255–1264. DOI: 10.1007/s11015-022-01271-9.

32. Adigamov R.R., Baraboshkin K.A., Mishnev A., Karlina A.I. Development of rolling procedures for pipes of K55 strength class at the laboratorial mill. *CIS Iron and Steel Review*, 2022, vol. 24, pp. 60–66. DOI: 10.17580/cisisr.2022.02.09.

33. Yelemessov K., Baskanbayeva D., Martyushev N.V., Skeeba V.Y., Gozbenko V.E., Karlina A.I. Change in the properties of rail steels during operation and reutilization of rails. *Metals*, 2023, vol. 13, p. 1043. DOI: 10.3390/met13061043.

Conflicts of Interest

The authors declare no conflict of interest.