APPLICATION OF INDUCTION HEAT TREATMENT TO PROVIDE CORROSION RESISTANCE OF STAINLESS STEEL WELDED PIPES

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The effect of induction heat treatment using currents with a frequency of 2.4 kHz on corrosion resistance of ∅85.6 × 0.6 and 142.9 × 0.9 mm welded pipes, made from chrome-nickel stainless steel 1.4301, at different proportions of heat treatment temperatures, heating rate, time of holding at the heat treatment temperature and cooling conditions was investigated. The use was made of specimens of the pipes after heating in single-turn inductors, as well as specimens of the long pipes that passed under current the entire length of the through-type multiple-turn inductors. The heat treatment parameters were chosen on the basis of their possible implementation in lines for production of thin-walled welded pipes at welding speeds of up to 0.063 m/s. It was shown that the heat treatment of the welded pipes in a temperature range of 700–770 °C, at heating rates of up to 47.7 °C/s and cooling rates of up to 12.5 °C/s leads to improvement of their corrosion cracking resistance, and does not deteriorate their intercrystalline and pitting corrosion resistance.
10 Ref., 1 Table, 4 Figures.

Keywords: *welded pipes, corrosion-resistant steel, heat treatment of pipes, corrosion cracking*

Small- and medium-diameter welded pipes made from corrosion-resistant steels of the austenitic grade are widely applied in oil and gas industries, as well as in heating and water supply systems. The low content of carbon in the steels decreases their sensitivity to pitting corrosion (PC) and intercrystalline corrosion (ICC) under the effect of environment [1]. The steels are characterised by satisfactory values of strength and toughness, and by good weldability. However, the technological operations of forming of an initial strip into a tubular billet, local heating of edges in welding and application of stiffeners, which are characteristic of production of welded pipes, lead to a change in structure and properties of the pipe metal. Formation of ferritic and martensitic phases, in addition to austenite, causes the probability of ICC or stress corrosion cracking (CC) [2].

Heat treatment (HT) is applied to provide maximal toughness and corrosion resistance, and to eliminate physical heterogeneity of pipes. The pipes are heated in furnaces with a controlled atmosphere, or in a conventional atmosphere followed by removal of scale. In particular, heating of the 08Kh18N10 steel pipes in a temperature range of 750–900 °C at a low holding and reduction of the heating time does not lead to a marked improvement of the CC resistance [3, 4]. At the same time, to achieve the highest resistance of pipes to ICC it is necessary to avoid the temperature of the beginning of intensive oxidation of steel. For steel 08Kh18N10 this temperature is 800–870 °C [5].

The time of heating of the pipes can be reduced by using the technology for induction heating with high-frequency currents. Generation of energy directly into the pipe metal provides a high heating rate in a range of the phase transformation temperatures that prevent growth of the austenite grain. Conditions for elimination of heterogeneity of volumetric changes can be created at an optimal proportion of the current frequency and pipe wall thickness. One of the advantages of the technology is the possibility of implementing it by the continuous-sequential method in welded pipe production lines [6–8]. A thin layer of oxides forming on the pipe surfaces at high heating rates can be readily removed. The induction equipment and automation means allow the specified HT parameters to be maintained at a high accuracy.

This study was performed to investigate the effect of induction HT using the 2.4 kHz frequency currents on corrosion resistance of welded pipes measuring ∅85.6 × 0.6 and 142.9 × × 0.9 mm, made from chrome-nickel stainless steel 1.4301. The efficiency of HT was estimated from the results of tests of the pipe specimens to the sensitivity to CC, ICC and PC.

Steel 1.4301, which is a close analogue of steel 08Kh18N10, belongs to non-ferromagnetic materials with relative magnetic permeability $\mu = 1$.

Characteristics of inductors and ranges of variations in parameters of HT of pipe specimens

Type of inductor	Parameter	Pipe size, mm	
		∅85.6 × 0.6	∅142.9 × 0.9
Single-turn	Length of current conductor, mm	95	120
	Diameter of current conductor (internal), mm	100	160
	Current frequency, kHz	2.1–2.3	2.0–2.2
	Transformation coefficient of matching transformer	22/1	22/1
	Compensating capacity, μF	85.6	116.0
	HT temperature, °C	440–950	500–1150
	Heating rate, °C/s	20.0–47.5	18.5–32.8
	Cooling rate, °C/s	1.75–4.81	1.54–12.50
	Holding at HT temperature, s	0–60	0–60
	Speed of pipes (expected), m/s	0.026–0.063	0.025–0.043
Through-type multiple-turn	Length of current conductor, mm	640	620
	Diameter of current conductor (internal), mm	120	170
	Quantity of current conductor turns	22	21
	Current frequency, kHz	1.95–2.10	1.92–2.05
	Transformation coefficient of matching transformer	13/4	13/4
	Compensating capacity, μF	66.0	52.3
	HT temperature, °C	540–850	500–780
	Heating rate, °C/s	7.2–10.0	8.1–11.3
	Cooling rate, °C/s	1.59–3.90	1.2–4.8
	Holding at HT temperature, s	10–20	15–20
	Speed of pipes (expected), m/s	0.0092	0.0083–0.014

The recommended current frequency for through heating of hollow cylindrical billets with an external diameter of up to 150 mm and wall thickness of up to 1 mm, made from the materials with $\mu = 1$, ranges from 0.5 to 8.0 kHz [9, 10]. At a current frequency of 2.4 kHz the depth of penetration of the current into the steel exceeds the pipe wall thickness. It can be assumed that the power through the pipe wall thickness is distributed uniformly, this leading to decrease in internal stresses.

Investigated were the pipe specimens after heating in single-turn inductors, as well as the specimens of long pipes that passed under the current along the entire length of through-type multiple-turn inductors. The frequency converter with a power of 160 kW and a rated frequency of 2.4 kHz, fitted with the transformer circuit for matching the converter with a load, was used as an induction heating source. Characteristics of the inductors and ranges of variations in parameters of HT of the pipe specimens are given in the Table. The effect of the HT temperature in a range of 440–750 °C, heating rate, time of holding at the HT temperature, cooling conditions and speed of movement of the pipes in the through-type inductors was evaluated. The working frequency of the heating source ranged from 1.95 to 2.30 kHz. Parameters of HT of the pipe specimens in the single-turn inductors, which are indicated in the Table, allow evaluating the expected parameters of HT of the long pipes in the through-type inductors. In particular, at a temperature of 750 °C, through-type inductor length of 1 m and heating rates of 18.5–47.5 °C/s the expected speed of the ∅85.6 × 0.6 and 142.9 × × 0.9 mm pipes in the through-type inductors will be 1.6–3.8 and 1.5–2.6 m/min, respectively.

Complex resistance of the single-turn inductors changes only insignificantly in heating of short specimens in these inductors. Some difference was observed in the dynamics of heating of specimens in the single-turn and through-type inductors. After the heating source reaches the specified power, the rate of heating of a specimen in the single-turn inductor remained unchanged during the entire heating time (Figure 1). A change in the heating rate was achieved by changing the specified power of the heating source. After switching off of the heating source upon reaching the HT temperature the time of natural holding of the specimens at the HT temperature did not exceed 3–5 s. Adjustment of the power of the heating source was applied to form a longer holding. In heating of the long pipes at their constant movement speed, the rate of heating of the specimens increased as they moved in the through-type inductors. A change in the HT temperature was achieved by changing the proportion of the pipe movement speed and power of the heating source. After the pipe specimens left the inductor-affected zone, the time of natural holding at the HT temperature amounted to 20 s. Forced air cooling of the pipes (fan productivity of 2700 m^3/h) at the exit of the through-type inductors was used to reduce the holding time. In particular, when heating the ∅85.6 × × 0.6 mm pipe to a temperature of 650–660 °C at their speed of 0.0092 m/s, the forced air cooling of the pipes led to reduction of the holding time from 20 to 10 s.

The CC resistance tests of the pipes were carried out in compliance with requirements of GOST 26294–84 «Welded Joints. Corrosion Cracking Test Methods». The pipe specimens in the initial state and after HT were held in 42 % solution of $MgCl_2$ at a boiling temperature of 154 °C. Formation of corrosion cracks was checked every 4–5 h. The CC resistance criterion was the time to formation of the first corrosion crack.

No corrosion cracks formed during the test time of 80 h after HT in the single-turn inductor (Figure 2) of the ∅85.6 × 0.6 mm pipe specimens at a temperature of 770–1070 °C, heating rate of 41.0–56.3 °C/s and natural cooling rate of 3.91–4.96 °C/s. The corrosion cracks appeared 10–66 h after HT of the pipe specimens in a temperature range of 440–640 °C at a heating rate of 20.0–39.2 °C/s, without holding, and at a natural cooling rate of 1.75–2.83 °C/s. No corrosion cracks were detected on the ∅142.9 × × 0.9 mm pipe specimens at the following HT parameters:

• 650–1100 °C temperature, 7.1–27.7 °C/s heating rate, without holding, 2.3–6.6 °C/s natural cooling rate;

• 1000 °C temperature, 6.4 °C/s heating rate, without holding, 9.3–12.5 °C/s forced air cooling rate;

• 960–1050 °C temperature, 6.7 and 29.1 °C/s heating rate, holding for 60 s, 5.36–5.50 °C/s natural cooling rate;

• 1100–1150 °C temperature, 7.1 and 32.8 °C/s heating rate, holding for 60 s, 10.7–12.1 °C/s forced air cooling rate.

It should be noted that no corrosion cracks were detected on the ∅142.9 × 0.9 mm pipe specimens at the heating rates varied within 6.4–7.1 and 18.5–32.8 °C/s, temperature of 960–1150 °C, cooling rates of 2.3–12.5 °C/s and holding for 60 s under the natural or forced air cooling conditions. Parameters of HT of such pipes in the single-turn inductors (960–1000 °C temperature, 23.8–29.1 °C/s heating rate, 5.18–5.50 °C/s natural cooling rate) corresponded to parameters of HT of the long pipes, 650 mm long, in the through-type inductors at their speed of about 0.025 m/s.

The corrosion cracks formed on the ∅142.9 × × 0.9 mm pipe specimens (see Figure 2) 10–66 h after HT in a temperature range of 500–600 °C, at heating rates of 21.7–25.0 °C/s, without holding, and at natural cooling rates of 1.54–2 °C/s.

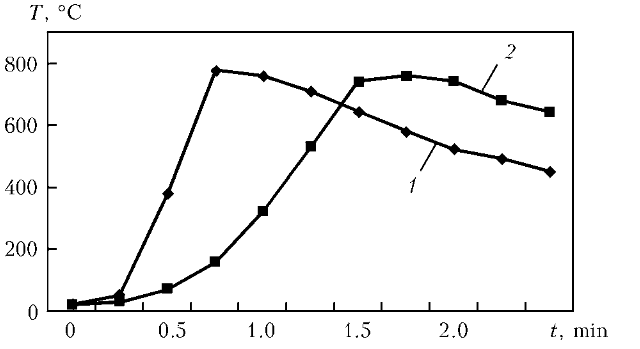

Figure 1. Dynamics of variations in temperature of pipe specimens during heating in single-turn (*1*) and through-type (*2*) inductors

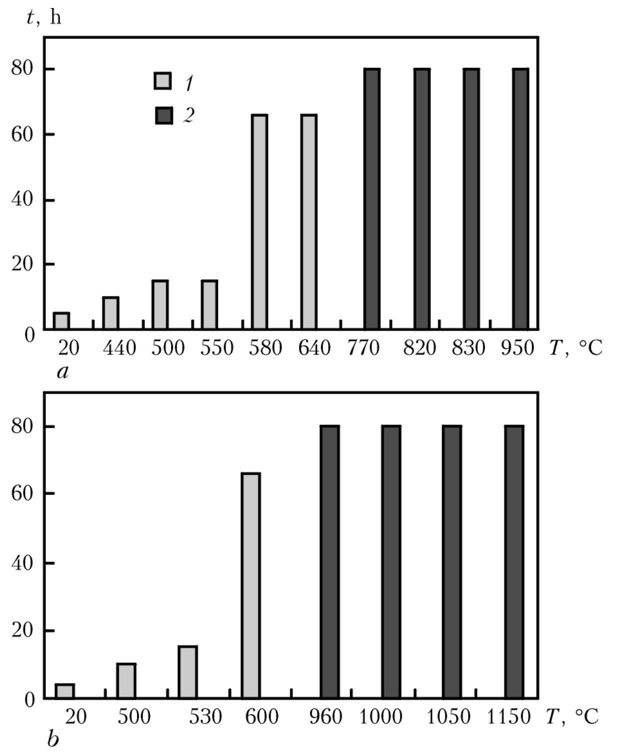

Figure 2. Dependence of time to formation of corrosion cracks on temperature of HT of the ∅85.6 × 0.6 (*a*) and 142.9 × 0.9 (*b*) mm pipe specimens heated in single-turn inductors: *1* — presence of cracks; *2* — absence of cracks

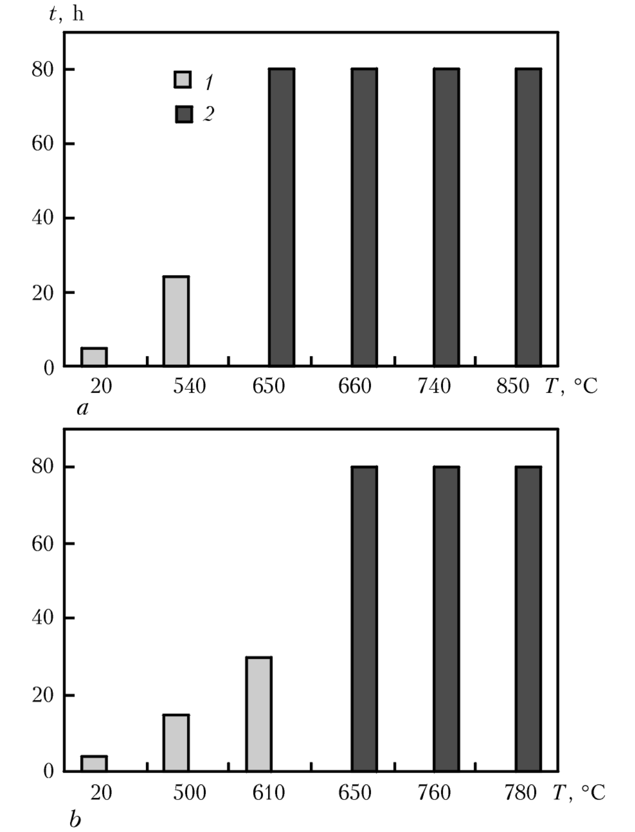

Figure 3. Dependence of time to formation of corrosion cracks on temperature of HT of the ∅85.6 × 0.6 (*a*) and 142.9 × 0.9 (*b*) mm long pipe specimens heated in through-type inductors: *1* — presence of cracks; *2* — absence of cracks

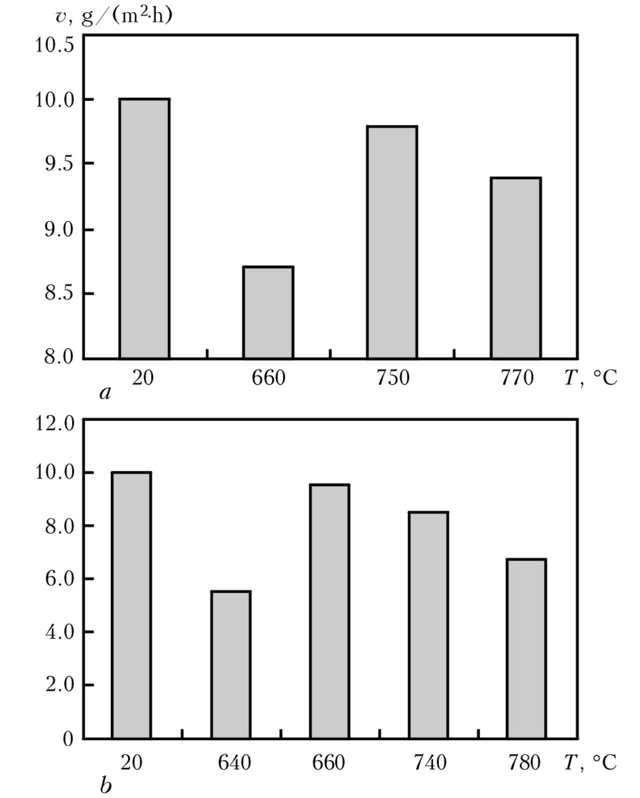

Figure 4. Effect of HT temperature on conditional average rate of PC of the ∅85.6 × 0.6 (*a*) and 142.9 × 0.9 (*b*) mm pipe specimens

On the ∅85.6 × 0.6 and 142.9 × 0.9 mm pipe specimens, which were not subjected to HT, the corrosion cracks appeared after 5 and 4 h, respectively. Therefore, the minimal temperature of HT of the ∅85.6 × 0.6 and 142.9 × 0.9 mm pipe specimens after heating in the single-turn inductors, above which no corrosion cracks formed, is 770 and 650 °C, respectively.

On the ∅85.6 × 0.6 mm, long pipe specimens the corrosion cracks formed 24 h after HT in the through-type inductor at a temperature of 540 °C, heating rate of 7.2 °C/s, natural cooling rate of 1.85 °C/s, and speed of 0.0092 m/s (Figure 3). The corrosion cracks did not form after HT at a temperature above 650 °C. On the ∅142.9 × 0.9 mm, long pipe specimens the corrosion cracks formed 15–30 h after HT at temperatures of 500 and 610 °C, heating rates of 8.7 and 8.1 °C/s, forced air cooling rates of 1.2 and 2.7 °C/s, and speed of 0.014 m/s. As a rule, a crack initiated at the absence of pitting. Therefore, the corrosion cracks did not form after heating of the ∅142.9 × 0.9 mm, long pipe specimens above 650 °C.

The tests to ICC were carried out according to GOST 6032–89 «Corrosion-Resistant Steels and Alloys. Intercrystalline Corrosion Resistance Test Methods» (item 3). The ICC resistance criterion was the absence of fracture at the grain boundaries to a depth of more than 10 μm. The pipe specimens were held in a boiling aqueous solution of 13 % $CuSO_4$ + 12 % H_2SO_4 at the presence of metal copper. The time of holding was 24 ± 0.25 h. No fractures along the grain boundaries were detected on the pipe specimens both in the base metal and in the weld zone after HT in the single-turn and through-type inductors. This is indicative of the ICC resistance of the pipe specimens.

The PC resistance tests of the pipe specimens were carried out in compliance with requirements of GOST 9.912–89 «Corrosion-Resistant Steels and Alloys. Accelerated Pitting Corrosion Resistance Test Methods». Allowing for the total loss of weight of three identical pipe specimens after holding in the 10 % solution of $FeCl_3$ for 24 h, the conditional average rate of PC of the pipe specimens not subjected to HT was v = = 10 g/(m^2·h) (Figure 4). Pittings propagated in the base metal. Isolated pittings had a through character. The welds contained isolated part-through pittings. The pipe specimens after HT in the single-turn and through-type inductors at a temperature of up to 780 °C had v = 5.2–9.8 g/(m^2·h). The quantity of pittings on the base metal and in the weld decreased. Mostly the weld experienced PC. It can be considered that HT did not deteriorate the PC resistance of the investigated pipe specimens.

Conclusions

1. HT of welded pipes with a diameter of up to 150 mm and wall thickness of up to 1 mm, made from chrome-nickel stainless steel 1.4301, in a temperature range of 700–770 °C, at heating rates of up to 47.7 °C/s, cooling rates of up to 12.5 °C/s, and speed of movement of up to 0.063 m/s leads to increase in CC resistance of the pipes, and does not deteriorate their ICC and PC resistance.

2. It is recommended to use induction heating with the 2.4 kHz frequency currents to conduct HT of thin-walled pipes from corrosion-resistant steels in lines for production of pipes by the argon-arc, electron beam and laser welding methods.

1. Semzin, V.N., Shron, R.Z. (1978) *Heat treatment and properties of welded joints*. Leningrad: Mashinostroenie.
2. Gulyaev, G.I., Vojtselenok, S.L. (1978) *Quality of welded pipes*. Moscow: Metallurgiya.
3. Sokol, I.Ya., Ulianin, E.A., Feldgandler, E.G. et al. (1989) *Structure and corrosion of metals and alloys:* Refer. Book-Atlas. Moscow: Metallurgiya.
4. Gulyaev, A.P. (1963) *Metals science*. Moscow: Oborongiz.
5. Borodulin, G.M., Moshkevich, E.I. (1973) *Stainless steel*. Moscow: Metallurgiya.
6. Krotkova, O.V., Chervinsky, V.I., Ratnikova, A.I. et al. (2010) Development of technology and equipment for induction heat treatment of corrugated stainless steel pipes. *Indukts. Nagrev*, **3**, 27–34.
7. Golovin, G.F., Zimin, N.V. (1979) *Technology of heat treatment of metals using induction heating*. Leningrad: Mashinostroenie.
8. Krotkova, O.V., Polyakov, S.G., Pismenny, A.S. et al. (2011) Influence of induction heating on corrosion resistance of thin-walled chrome-nickel steel pipes. *Stal*, **3**, 57–60.
9. Slukhotsky, A.E., Ryskin, S.E. (1974) *Inductors for induction heating*. Leningrad: Energiya.
10. (1980) *Thermal-electric equipment:* Refer. Book. Ed. by A.P. Altgauzen. Moscow: Energiya.

Received 01.04.2013