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PECULIARITIES OF WELDING COMBINED JOINTS OF 15Kh2M2FBS (P3) AND X10CrMoVNb91 (P91) STEELS

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ABSTRACT

Within the framework of currently urgent problem of reconstruction and restoration of equipment of thermal power units of TPP, work has been performed on development of basic technology of welding body elements of a steam turbine from low-alloyed 15Kh2M2FBS (P3) steel to branchpipes from high-chromium martensitic X10CrMoVNb91 steel with 9 % Cr (P91). The paper gives the results of determination of the thermal mode of welding such combined joints to prevent delayed fracture. Proceeding from study of the influence of different modes of high-temperature tempering on impact toughness of weld metal and hardness of welded joint areas hardened during welding, heat treatment modes were selected, depending on electrode material type. It is shown that the resultant mechanical properties of welded joints correspond to the requirements, specified during work performance.

KEYWORDS: heat-resistant steels, low-alloyed steel, high-chromium martensitic steel, combined welded joints, cold cracks, high-temperature tempering, mechanical properties

INTRODUCTION

As shown by information sources, at present boiler equipment of TPP power units is in an unsatisfactory condition. Its general characteristics include moral obsolescence of project technologies, considerable wear of the equipment (for instance, exceeding the "physical wear limit of 200 thou h" approximately in 80% of power units), limiting the working parameters of the heat carrier for the reason of insufficient heat-resistance of steels, problems of cleaning from pollutant emissions, in particular meeting the current requirements to greenhouse gas emissions, etc. [1].

Considering the current problems in the energy sector [1, 2] and economic capabilities of Ukraine, it is rational, alongside construction of new power sources, to conduct timely repairs and reconstruction of the equipment, using advanced technological solutions and improved structural materials. As regards components, exposed to high temperatures and pressures in service, new modifications of high-chromium steels can be used, having higher long-term strength and corrosion resistance under the working conditions, than the traditional low-alloyed steels. At the present stage, steel with 9 % Cr of P91 (X10CrMoVNb91) type can be the most probable candidate material for work on reconstruction of boiler units. This steel, as well as its new modifications are being studied and are becoming widely applied in the world practice in manufacture of high-temperature components of thermal power units [3, 4]. The advantages of application of such steels is the possibility of raising the working parameters of the heat carrier (up to the temperature of 600–620 °C, pressure up to 31 MPa), reduction of the structure weight, while ensuring their higher reliability in service.

In the proposed work the results of development of the technology of welding tubular elements (branchpipes) from P91 steel to the steam turbine body from low-alloyed steel P3 (15KhM2FBS) are given as an example of upgrading the power equipment. The work was performed in cooperation with JSC "Ukrenergymachines" (former JSC "Turboatom").

MATERIALS AND METHODS OF INVESTIGATION

Chemical composition of the used steels is given in Table 1. For welding their combined joint, electrodes with deposited metal alloying close to the composition of each steel were selected (Table 2). Before application, the electrodes were baked by the mode, recommended by the manufacturer (Böhler Thyssen Schweisstechnik), at 300–350 °C, 2 h. Quantity of diffusible hydrogen H_{dif} was determined by alcohol analysis, using "pencil" samples of electrode metal, deposited into a copper chill mould [5]. For Thermanit Chromo 9V electrodes, H_{dif} was equal to 0.117–0.5, for Thermanit P24 it was 0.582–1.9 $cm^3/100$ g. Considering the susceptibility of steels to hardening, the influence of the thermal mode of welding (preheating) on prevention of delayed fracture was evaluat-

Table 1. Chemical composition of heat-resistant steels used in the work, wt.%

Steel	C	Si	Mn	S	P	Cr	Ni	Mo	V	Nb
П3	0.115	0.468	0.67	0.023	0.027	1.95	0.16	1.12	0.32	0.072
P91	0.085	0.33	0.43	0.015	0.013	8.85	0.12	1.0	0.25	0.069

Table 2. Chemical composition of electrode metal, wt.%

Electrode grade	C	Si	Mn	S	P	Cr	Ni	Mo	V	Nb	Ti
Thermanit Chromo 9V	0.12	0.1	0.55	<0.001	0.010	9.0	0.75	0.98	0.25	0.038	0.006
Thermanit P24	0.11	0.1	0.33	<0.001	0.011	2.6	0.01	0.90	0.20	0.028	0.002

ed, using traditional test methods — Implant test and welding of rigid butt joints of Tekken type with asymmetrical Y-shaped groove in the control zone (DSTU EN ISO 17642-2, DSTU EN ISO 17642-3 [6, 7]). Implant samples (of 8 mm dia) had a spiral stress raiser at the end of the working part, which is welded to the plate, having the form of a groove of V-shaped profile 0.5 mm deep with 40° opening angle and 0.1 mm rounding-off radius at the tip (in keeping with DSTU EN ISO 17642-3). Here, at Implant tests the preheating temperature was measured by the potentiometer and thermocouple of XA type (in a protective ceramic sheath), passed through an opening in the supporting plate and welded to the sample by a capacitor-discharge machine [8]. At Tekken tests and welding of control butt joints a contact thermocouple of the same type with KSP4 potentiometer was used. Mechanical properties were determined in keeping with the provisions of the current standards on static tensile testing (of weld metal and welded joints according to DSTU EN-ISO 5178:2015, DSTU EN ISO 4136:2014), impact testing of welds (DSTU EN ISO 9016:2019) and static bend testing of welded joints (DSTU EN ISO 5173:2019). Vickers hardness was measured at 5 kg load. Samples prepared in keeping DSTU ISO 204:2019 were used to assess the long-term strength (of weld metal and welded joints). Test samples were prepared from combined butt joints of steels P3–P91 20 mm thick with 30° bevel. Welding was performed with both types of studied electrodes in the following modes: for root passes — current I_w = 95–105 A, voltage U_a = 24 V, welding speed v_w ~ ~ 5 m/h; for filling passes – I_w = 130–140 A, U_a = 24 V, v_w ~ 16–20 m/h; preheating specified by experimental results (see furtheron) was equal to 200–230 °C. Metallographic studies of the microstructures were conducted using light microscope Neophot-32.

RESULTS AND THEIR ANALYSIS

During work performance the main objective was to ensure both the welded joints resistance to delayed fracture (cold cracks) that is always required in welding of hardenable steels, and weld metal impact toughness not lower than 51 J/cm^2 (41 J [6]) at their strength not lower than that of the base metal.

Thermal mode of welding is known to be the main technological factor in counteracting the delayed fracture, alongside limiting the concentration of diffusible hydrogen, penetrating into the weld. The mode, in its turn, is controlled by preheating/accompanying heating of metal in the joint zone. Figure 1 gives the results of quantitative evaluation of the influence of preheating on the studied steel resistance to this kind of fracture, obtained by Implant test. The criterion is maximal–critical–stresses, exceeding which leads to the joint damage.

Results of testing joints of P3 steel show that preheating to approximately 100 °C does not affect the fracture resistance. Critical stresses remain on the same level, as in welding without preheating. However, at preheating up to 150 °C and higher, cracking

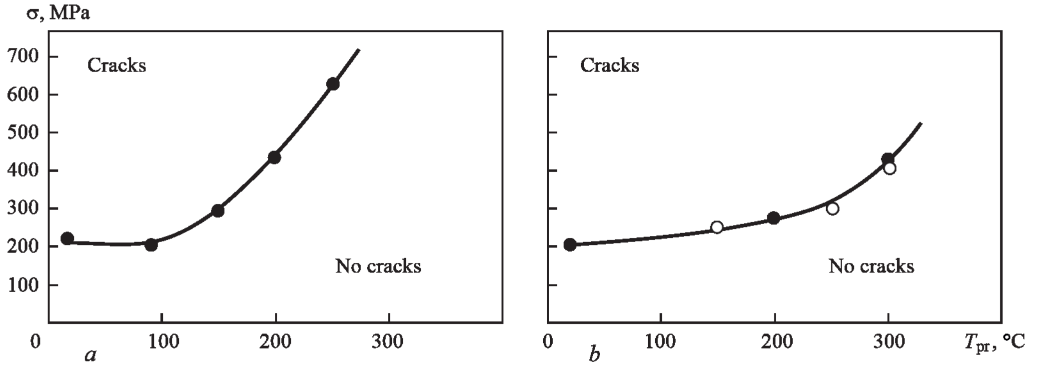

Figure 1. Influence of preheating temperature at Implant tests on critical stresses causing delayed fracture of welded joints: *a* — P3 steel; Thermanit P24 electrodes; *b* — P91 steel, ThermanitChromo 9V electrodes

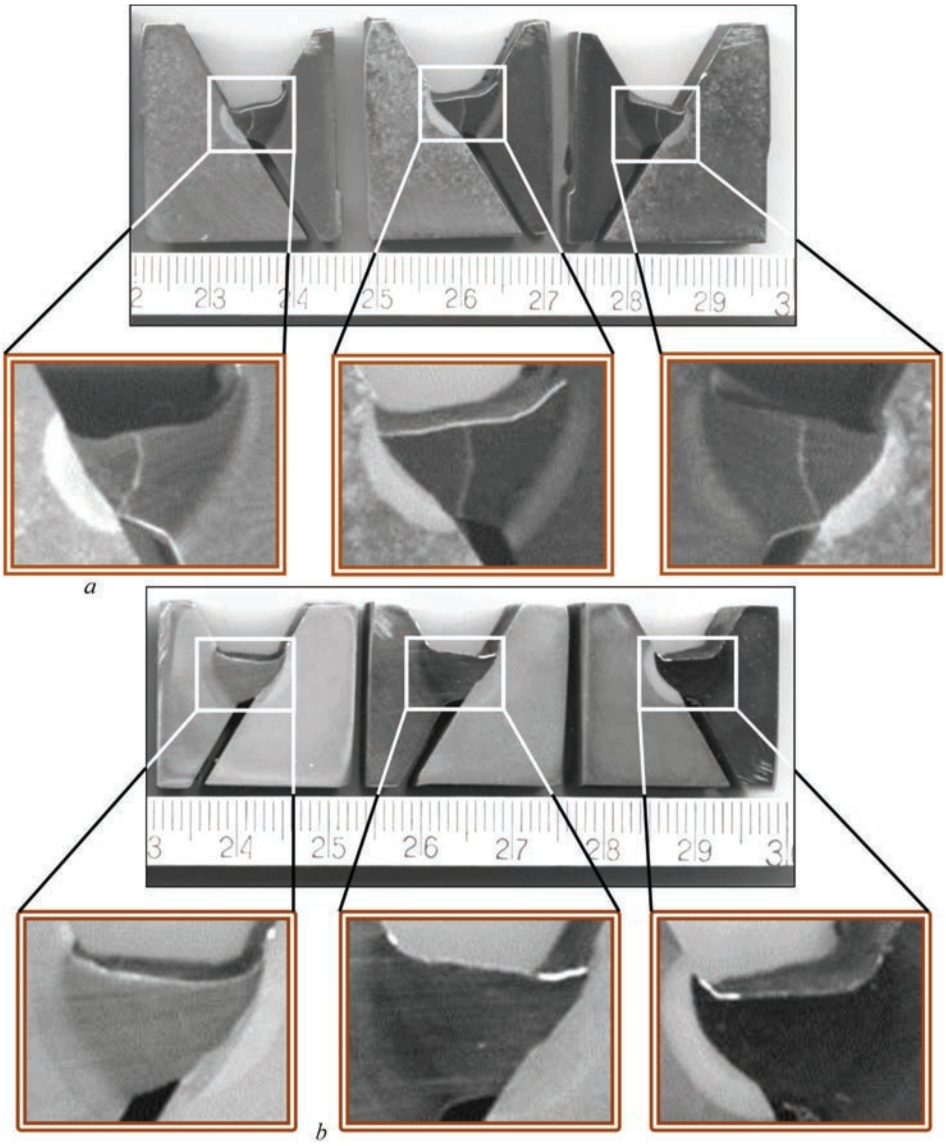

Figure 2. Transverse sections cut out of Tekken joints: *a* — Thermanit P24 electrode; T_{pr} = 150 °C (cracks); *b* — Thermanit Chromo 9V electrode T_{pr} = 150 °C (no cracks)

resistance rises abruptly. It confirms the rationality of welding P3 steel with preheating to more than 150 °C.

In the joints of martensitic steel P91, an increase of cracking resistance intensity is observed at the temperature above 200 °C. Under the above-mentioned conditions, however, these joints can stand lower critical stresses than P3 steel joints, i.e. the martensitic complex-alloyed chromium steel has higher delayed cracking resistance than does P3 steel. In view of this fact, when producing combined joints of both the steels, such a thermal mode should be used, which reduces the risk of cracking in welding chromium steel proper. As one can see from the results of Implant tests (Figure 1, *b*) it can be preheating to 200–250 °C.

As Implant tests allow loading the welded joints to stresses, which may not correspond to stresses in the real joints and may be much higher, the delayed fracture resistance was checked using technological samples — Tekken butt joints. Two combined joints of P91 + P3 steels were used for each thermal mode, in which each steel had one and two bevels, (taking into account the asymmetric Y-shaped configuration of the edges in the butt). After welding the joint was kept for not less than 24 h before further testing. Presence of cracks was determined visually at examination of the butt surface and studying in the light microscope the transverse templates cut out of the joint, ground and chemically etched to reveal the macrostructure (Figure 2). The obtained data are given in Table 3.

Generalizing results of testing for technological strength, preheating up to and maintaining the interpass temperature of 175–250 °C can be regarded as sufficient. In welding joints of a large cross-section and under the conditions of intensive heat removal, the preheating temperature should be increased (up to 250–300 °C) to prevent its decrease in the welding zone below the specified minimal level.

Table 3. Results of welding butt combined Tekken samples from P3 + P91 steels

Preheating temperature T_{pr}, °C	Thermanit chromo 9V weld (9 % Cr)	Thermanit P24 weld (2.5 % Cr)
	Presence of cracks	
150	Yes*	No
175	No	No
200	No	No

*Crack in the weld.

In welding hardenable steels tempering is the main technological technique of regulation of the mechanical properties, structural and stressed state. This operation, however, becomes problematic at heat treatment of combined joints of steels with considerable differences in alloying, when different modes are recommended for each of them, and particularly, in the absence of coincidences in the temperature ranges of recommended tempering. In such cases, the technology of producing the joints becomes much more complicated: it becomes necessary to use metals of intermediate composition (welded metal or inserts of other steels) and heat treatment in several stages. This topic will be considered in a separate publication.

Proceeding from literature and reference data, tempering of P3 steel can be conducted at 730–750 °C, of steel P91 — at 750–760 °C (according to [10], the range can be wider: from 740 to 780 °C). As recommended by electrode manufacturer (Böhler Thyssen), 740 °C is the most favourable for weld metal of Thermanit P24 type, and for Thermanit Chromo 9V type it is 760 °C. For all the materials in the combined joint the range of close tempering temperatures is equal to 740–750 °C.

The final heat treatment mode needed to be precised, considering the following conditions: 1) tempering at a higher temperature gives a greater guarantee of obtaining the required properties and in a shorter time; 2) increase of tempering temperature for metal with a limited maximum heating temperature may lead to its greater softening; 3) known “inertness” of welds of P91 type as to increase of ductility and impact toughness requires application of higher temperatures, tempering at lower temperatures restrains these indices reaching the required level and may require increase of tempering duration.

In this regard, a study was carried out on the influence of heat treatment modes on impact toughness of weld metal, metal hardness in the joint zone and resulting mechanical properties. Considering prior experience and literature data, tempering was conducted with different soaking at temperatures of 740, 750 and 760 °C. Lower temperature was not used, because of the possibility of obtaining unsatisfactory results for weld of P91 type.

The primary task was to ensure the impact energy of the more problematic martensitic chromium welds below the criterial value of 41 J (KCV = 51 J/cm^2). Also taken into account was tempering mode influence on HAZ metal hardness becoming closer to that of the base metal, which was taken as an approximate criterion of achieving a uniform structural state and mechanical properties of the metal of near-weld zone.

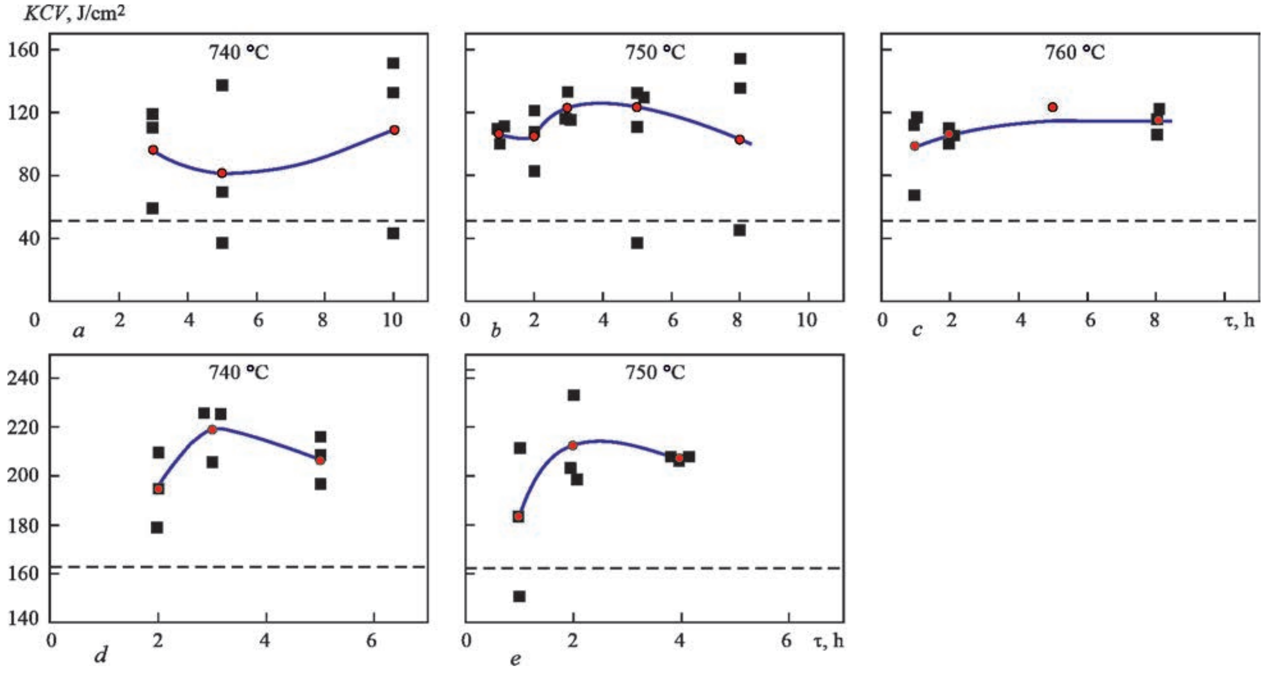

Figure 3. Influence of tempering mode on impact toughness of weld metal in P3 + P91 steel welded joints: *a–c* — welding with Thermanit Chromo 9V electrodes; *d*, *e* — welding with Termanit P24 electrodes

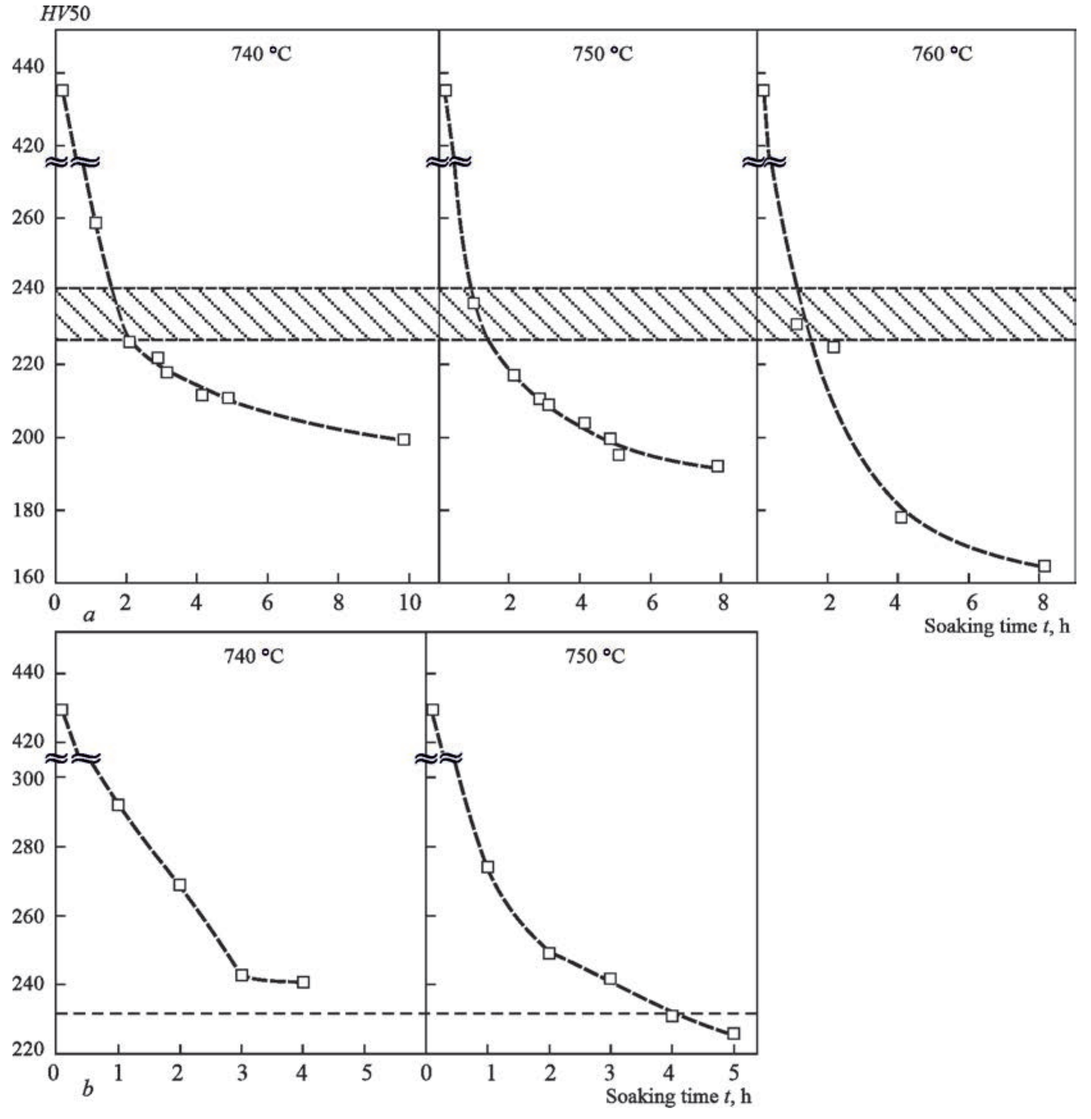

Figure 4. Influence of temperature and duration of postweld tempering on HAZ metal hardness in the area of hardening of P3 + P91 steel welded joints (welding with Thermanit Chromo 9V electrodes): *a* — metal hardness in P3 steel HAZ; *b* — metal hardness in P91 steel HAZ

Obtained test results are given in Figures 3–6. In Figure 3 dashed lines show the target levels of impact toughness: specified minimum for martensitic welds with 9 % Cr (Figure 3, *a*–*c*) and averaged level, which, by the data of electrode manufacturer, is usually provided by welds of P24 type (Figure 4, *d*, *e*).

Proceeding from the derived regularities, at the change of impact toughness the following can be regarded as favourable modes:

1) for joints made by Thermanit Chromo 9V electrodes:

- 740 °C, 2–3 h;
- 750 °C, 1–2 h;
- 760 °C, 1 h.

2) for joints made by Thermanit P24 electrodes:

- 740 °C, 2 h;
- 750 °C, 1 h.

For the above modes, the obtained average *KCV* exceed the target level for both weld types. Meanwhile, for 9 % Cr welds treated at 740 °C, an increased scatter of test results and possibility of individual *KCV* values dropping to minimal level is observed (Figure 3, *a*). On the whole, however, in view of the data on the admissibility of lowering of impact energy for chromium welds to 27 J (or *KCV* to 34 J/cm^2) [11, 12], such results can be considered acceptable.

As one can see from Figures 4, 5, the studied steels demonstrate different sensitivity to temper heating that can be traced by the nature of the change of hardness values of hardened HAZ metal. So, in P3 steel at all the temperatures the hardness drops abruptly and reaches base metal level (240–225 *HV*) approximately in 1–1.5 h. At minimal temperature (740 °C) soaking for more than 3–4 h leads to a noticeable lowering of hardness below this level. A more significant softening takes place at transition to tempering at 750 and 760 °C, starting from soaking for more than 2 h. Hardened regions of P91 steel undergo less intensive

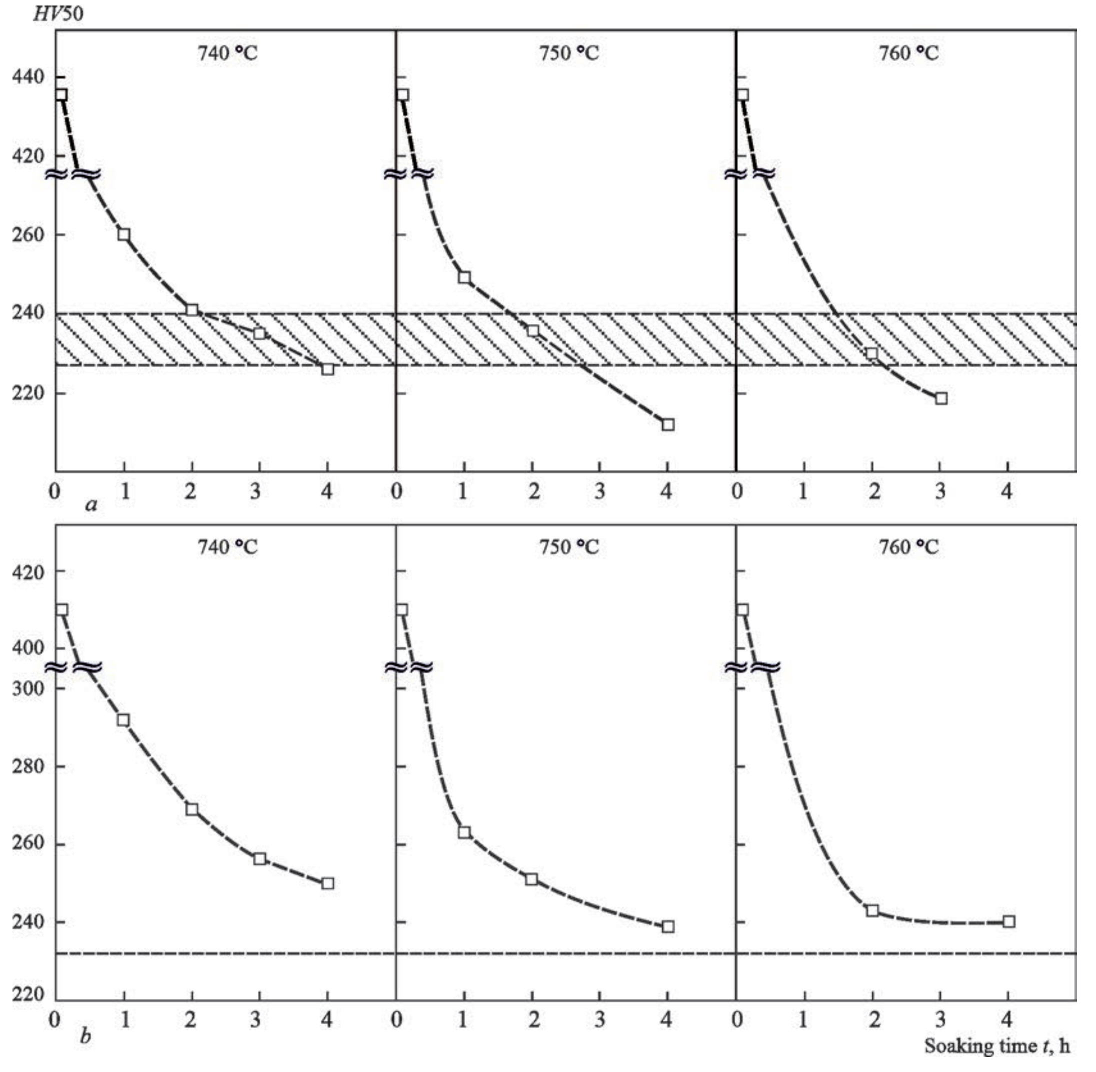

Figure 5. Influence of temperature and duration of postweld tempering on HAZ metal hardness in the area of hardening of P3–P91 steel welded joints (welding with Thermanit P24 electrodes): *a* — HAZ metal hardness in P3 steel; *b* — HAZ metal hardness in P91 steel

tempering. In the used modes, hardness is gradually lowered to the level close to base metal initial hardness (233 *HV*), while remaining somewhat greater, as one can see from the data obtained at 740 °C. No significant softening after long-term soaking (4–5 h) at higher temperatures (750, 760 °C) was found. The nature of the change of weld metal hardness in different modes is close to the change of HAZ metal hardness (Figure 6).

Note that practical experience of tempering welded joints of some heat-resistant hardening steels envisages application of temperatures by 20 to 40 °C lower

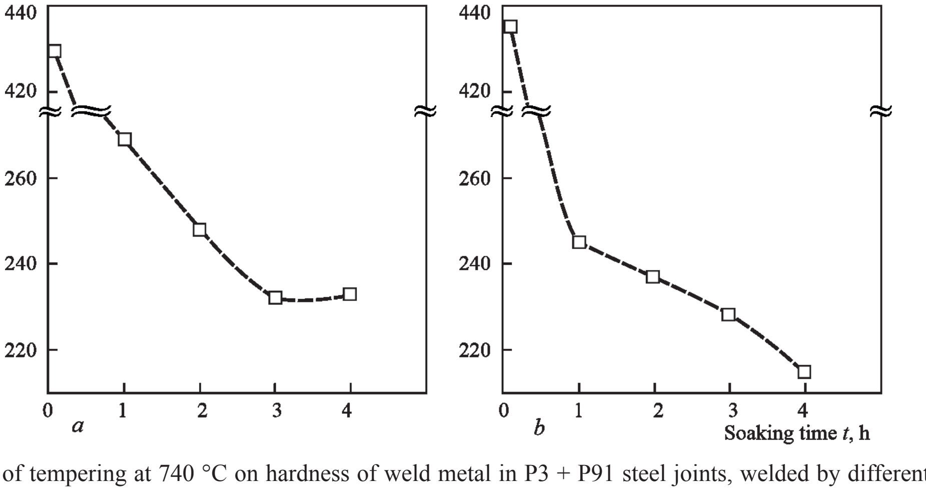

Figure 6. Influence of tempering at 740 °C on hardness of weld metal in P3 + P91 steel joints, welded by different electrodes: *a* — Thermanit Chromo 9V electrodes with 9 % Cr; *b* —Thermanit P24 electrodes with 2.25 Cr %

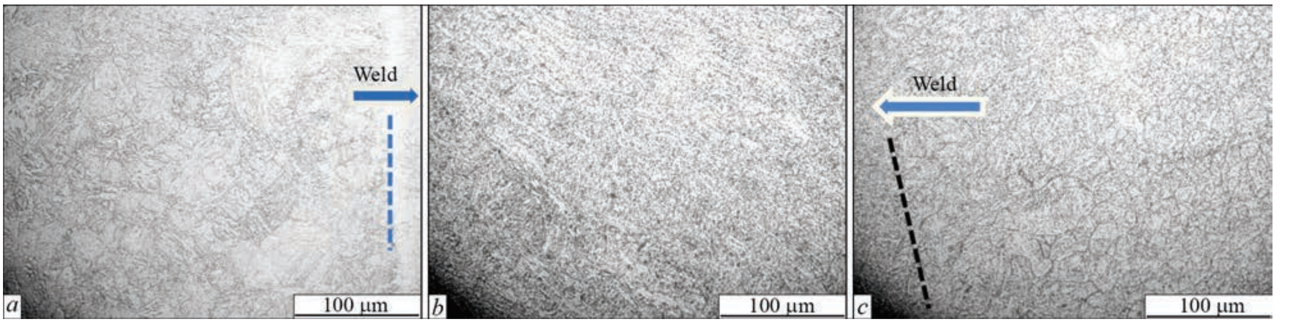

Figure 7. Microstructure of a joint welded with Thermanit Chromo 9V electrodes: *a* — HAZ and area of fusion of P3/weld; *b* — weld metal; *c* — HAZ metal and area of fusion of P91/weld

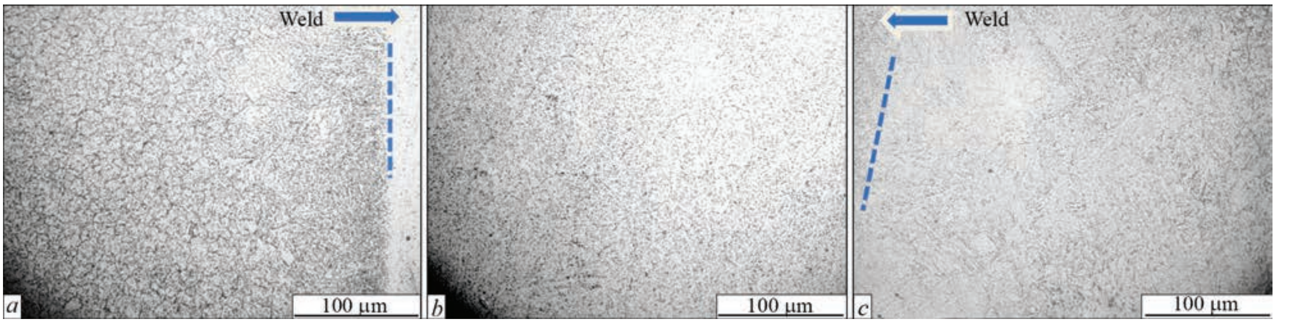

Figure 8. Microstructure of a joint (×400) welded with Thermanit P24 electrodes: *a* — HAZ and area of fusion of P91/weld; *b* — weld metal; *c* — HAZ metal and area of fusion of P3/weld

than the steel tempering temperature in its production. The objective of this measure is prevention of further structural changes and possible lowering of the initial strength characteristics of base metal. Under such conditions, HAZ metal hardness will be higher than that of steel in as-delivered condition. Moreover, in keeping with DSTU ISO 15614-1 standard, hardness of metal in martensitic chromium steel welded joints should not be higher than 350 *HV*, i.e. higher hardness of HAZ metal from the side of P91 steel that is observed at lower tempering temperature (as at 740 °C) should not be regarded as a rejection characteristic.

Considering the conditions for ensuring the necessary level of weld impact toughness, limitation of overheating of base metal and metal in the welded joint zone, the following modes of tempering the combined P3–P91 joint were selected: in welding with Thermanit Chromo 9V electrodes — 740 °C, 3 h, and with Thermanit P24V electrodes — 740 °C, 2 h.

Verification of the specified technological measures consisted in evaluation of the quality and mechanical properties of control butt joints produced with application of both the selected electrode types. Welding was performed with preheating to 200 °C and interpass temperature of up to 230 °C, tempering — by the above-given modes. Quality was evaluated visually and by metallographic examination of transverse microsections. Results of visual examination and metallographic analysis confirmed absence of cracks in welded joints. No pores, slag inclusions, lacks-of-fusion were found (Figures 7, 8). In as-tempered condition, hardness of both types of welds was on the level of 230 *HV*.

Mechanical properties of welds and welded joints after short-term tensile and impact bend testing are given in Table 4. Tensile testing of transverse samples showed that weld strength was higher than that of base metal at room and working temperatures: all the samples broke through the HAZ metal. At static bending through an angle of 120° (Figure 9), no defects developed in the joints.

For maximum operating temperature (570 °C), the value of long-term strength limit of the metal of welds and welded joints was obtained by direct testing for periods of 10^3 and 10^4 h and by approximation method — for 10^5 h (Table 5). In all the cases of testing transverse samples of welded joints fracture ran through the HAZ

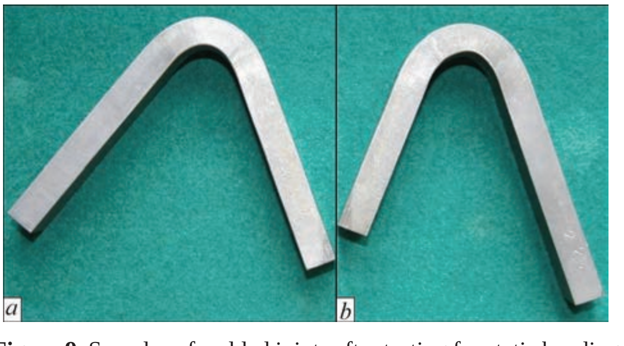

Figure 9. Samples of welded joints after testing for static bending at 20 °C: *a* — Thermanit Chromo 9V weld; *b* — Thermanit P24 weld

Table 4. Mechanical properties of combined welded joints

Electrode grade	T_{test}, °C	Weld metal*					Welded joint	
		$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KCV*, J/cm²	σ_t, MPa	Fracture area
Thermanit Chromo 9V	20	601.0 602.5 (601.8)**	729.0 725.3 (727.2)	20.0 17.0 (18.5)	64.8 40.2* (64.8)	110.1 119.7 59.1 (96.3)	617.4 613.7 (615.6)	P3 HAZ metal P3 HAZ metal
	570	376.9 345.9 (361.4)	407.9 394.0 (401.0)	20.3 24.7 (22.5)	79.8 82.7 (81.3)	– –	353.6 366.9 (360.3)	P91 HAZ metal P91 HAZ metal
Thermanit P24	20	621.7 618.5 (620.1)	714.7 718.6 (716.7)	21.0 19.7 (20.4)	67.6 69.7 (68.7)	178.9 209.0 193.8 (193.9)	666.0 669.5 (667.8)	P3 HAZ metal P91 HAZ metal
	570	409.9 411.2 (410.6)	447.5 454.4 (451.0)	19.3 21.7 (20.5)	79.8 81.2 (80.5)	– –	396.2 383.7 (390.0)	P91 HAZ metal P91 HAZ metal

*Rupture near the working zone edge.
**Average value is given in the brackets.

Table 5. Results of long-term strength testing of composite welded joints of P3 + P91 steels

Sample type	Long-term strength limit (MPa) and fracture site				
	In 10^3 h	Fracture site	In 10^4 h	Fracture site	In 10^5 h
Thermanit P24 deposited metal	193	–	147	–	112
Welded joint, Thermanit P24 weld	147	P3 HAZ metal	94	P3 HAZ metal	60
Thermanit Chromo 9V deposited metal	209	–	187	–	167
Welded joint, Thermanit Chromo 9V weld	152	P3 HAZ metal	87	P3 HAZ metal	50

metal of low-alloyed P3 steel. Weld metal had much higher fracture resistance than base metal.

CONCLUSIONS

1. It is shown that prevention of delayed fracture of the combined joints of P3 + P91 steels in welding by Thermanit Chromo 9V or Thermanit P24 electrodes can be achieved at preheating do not lower than 175 °C.

2. Proceeding from the conducted investigations, the following high-temperature tempering modes are recommended, depending on the applied type of welding electrodes: 740 °C, 3 h (Thermanit Chromo 9V electrodes) and 740 °C, 2 h (Thermanit P24 electrodes).

3. Welding of control combined joints confirmed that application of the proposed heat-treatment welding modes and high-temperature tempering provides absence of cold cracks, relatively homogeneous tempering structure with hardness of 220–240 *HV* of prehardened regions of welded joints, high impact toughness of weld metal (98 J/cm² for Thermanit Chromo 9V welds and 190 J/cm² for Thermanit P24 welds on average) and their higher short-term (at 20 °C) and long-term strength (at 570 °C) than that of base metal.

4. The developed welding process was accepted at JSC "Ukrenergymachines" for practical application.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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