ISSN 0040-6015, Thermal Engineering, 2016, Vol. 63, No. 7, pp. 471–480. © Pleiades Publishing, Inc., 2016.
Original Russian Text © E.A. Grin', A.E. Anokhov, A.V. Pchelintsev, E.-T. Krüger, 2016, published in Teploenergetika.

95TH ANNIVERSARY OF THE ALL-RUSSIA THERMAL ENGINEERING INSTITUTE

Study of the Structure and Properties of Metal of the Major Steam Lines of a CCGT-420 Unit Made from High-Chromium X10CrMoVNb9-1 (P91) Steel

E. A. Grin'[a], A. E. Anokhov[a, *], A. V. Pchelintsev[a, **], and E.-T. Krüger[b]

[a]*All-Russia Thermal Engineering Institute, ul. Avtozavodskaya 14, Moscow, 115280 Russia*
[b]*FINOW Rohrsysteme GmbH, Angermünder Str. 101, D-16225 Eberswalde, Germany*
**e-mail: aanokhov@yandex.ru*
***e-mail: apchelincev@mail.ru*

Abstract—The technology of manufacture of live steam lines and hot reheat lines at FINOW Rohrsysteme GmbH are discussed. These pipelines are designed for high-performance CCGT units and are made from high-chromium martensitic steel X10CrMoVNb9-1 (P91). The principles of certification and evaluation of conformance of thermal and mechanical equipment made from new construction materials with the TRCU 032-2013 technical regulation of the Customs Union are detailed. The requirements outlined in Russian and international regulatory documents regarding the manufacture of pipes and semifinished products for pipeline systems are compared. The characteristic features of high-chromium martensitic steel, which define the requirements for its heat treatment and welding, are outlined. The methodology and the results of a comprehensive analysis of metal of pipes, fittings, and weld joints of steam lines are presented. It is demonstrated that the short-term mechanical properties of metal (P91 steel) of pipes, bends, and weld joints meet the requirements of European standards and Russian technical specifications. The experimental data on long-term strength of metal of pipes from a live steam line virtually match the corresponding reference curve from the European standard, while certain experimental points for metal of bends of this steam line and metal of pipes and bends from a hot reheat line lie below the reference curve, but they definitely stay within the qualifying (20%) interval of the scatter band. The presence of a weakened layer in the heat-affected zone of weld joints of steel P91 is established. It is shown that the properties of this zone govern the short-term and long-term strength of weld joints in general. The results of synthesis and analysis of research data support the notion that the certification testing of steam lines and other equipment made from chromium steels should necessarily involve the determination of long-term strength parameters.

Keywords: combined-cycle gas turbine, high-chromium steel, major steam lines, fittings, welds, regulatory documents, certification tests, microstructure, mechanical properties, long-term strength

DOI: 10.1134/S0040601516070028

The international experience accumulated in the development of thermal engineering suggests that combined-cycle gas turbines (CCGTs) are currently one of the most efficient heat-generation units. Traditional steam-power units are less efficient: their maximum efficiency is approximately 42%, and modern CCGT units are at the level of 58% [1]. State-of-the-art European (Eemshaven, Maasvlakte) steam-power units with an output of 800 and 1100 MW have demonstrated an efficiency of 45% in their acceptance tests, while the efficiency of new-generation CCGTs with an output of 550 MW (Irsching IV) exceeds 61%. In addition to high efficiencies, CCGTs offer a relatively low cost of unit installed capacity, prompt operational commissioning, high flexibility, and improved environmental performance. In view of this, several such units were commissioned in recent years at the electric power plants of PAO Mosenergo and the power stations in Shatura, Yaiva, Nizhnevartovsk, etc.

The high efficiency of combined-cycle gas turbines is attained due in no small part to the enhanced parameters of steam in the steam-power CCGT section. For example, the superheated steam temperature in the majority of CCGT units is approximately 570°C (in both circuits). The enhancement of steam parameters necessitates an appropriate choice of construction materials for the fabrication of high-temperature assemblies and elements of the steam-power section. At operating temperatures in excess of 560–565°C, it is economically and technically viable to use steels with an enhanced elevated-temperature strength to fabricate the indicated elements (specifically, live steam (LS) lines and hot reheat (HRH) lines). At temperatures higher than 570°C, the use of such steels (e.g., chromium martensitic steels) is a mandatory requirement.

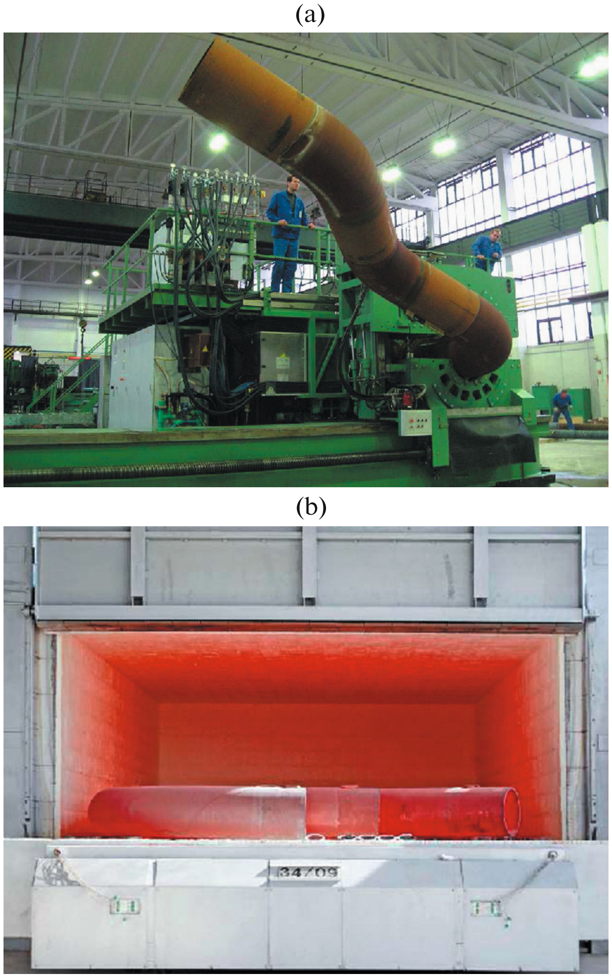

Fig. 1. Manufacture of bends at the FINOW Rohrsysteme GmbH facility: (a) bending machine and (b) furnace for heat treatment.

Martensitic steels offer higher elevated-temperature strengths than pearlite ones, thus providing an opportunity to reduce the overall mass and rigidity of a pipeline system by making the walls thinner [2]. In addition, the enhanced elevated-temperature strength reduces the risk of wheelspace damage by scale. At operating temperatures in the interval of 565–600°C, it is advisable to choose 9%-chromium steel 10Kh9MFB (DI-82) or its equivalent X10CrMoVNb9-1 (P91) from the range of martensitic steels.

OBJECT UNDER STUDY

Combined-cycle gas turbines at TETs-16 and TETs-20 operated by Mosenergo were constructed based on gas (288 MW) and steam (160 MW) turbines that were manufactured and supplied by Siemens for two CCGT units with an output of 420 MW. At the design stage, the engineers at Mosenergo have analyzed various constructions of the major steam lines for the power unit of TETs-16. It was decided following the assessment of a combination of factors (cost, quality, reliability, time of manufacture, etc.) that LS and HRH lines should be made from P91 steel, and FINOW Rohrsysteme GmbH (FINOW) should be granted the contract for manufacture of the major elements and units. This decision was later extended to the CCGT-420 unit for TETs-20.

FINOW (Eberswalde, Germany) has more than 100 years of experience in the manufacture of pipeline systems and has been the largest supplier of such products to the energy and chemical industry of the German Democratic Republic. In 2007, this company joined the leading European consortium Kraftanlagen München GmbH that specializes in the construction of electric power plants. In 1987, FINOW introduced modern induction heating technology into the process of bending. Induction bends are manufactured using two bending machines (see Fig. 1a) that are capable of bending pipes with a diameter of up to 440 mm and a wall thickness of up to 70 mm (Cojafex PB Special) and with a diameter of up to 1220 mm and a wall thickness of up to 120 mm (Cojafex IBM PB 1200). The bend length may reach 12 m, and the bend angle may be as large as 180°. Pipe units are subjected to heat treatment in two furnaces with the maximum temperature of 1200°C. These furnaces (see Fig. 1b) have the following maximum load and dimensions of the active area: 16 t and 9100 × 5100 × 2000 mm (furnace no. 1) and 40 t and 11 800 × 6500 × 2300 mm (furnace no. 2).

While working on the project on manufacturing the steam lines for the CCGT-420 unit for TETs-16, FINOW requested the services of the All-Russia Thermal Engineering Institute (OAO VTI) as an expert organization that would analyze the state of production, assess the quality management system, and verify the performance parameters of produced parts and units in order to obtain the Rosthekhnadzor permit for their use in the construction of steam lines. FINOW was granted this permit in 2013 on the grounds of an expert report drawn up by OAO VTI, which was also involved later in the project on manufacturing the steam lines for CCGT-420 at TETs-20. However, owing to legislative amendments (the implementation of the TRCU 032-2013 technical regulation of the Customs Union), a conformance certificate was needed then instead of a permit in order to verify the quality of manufactured articles. The entire required scope of work was performed by OAO VTI, and the certificate of conformance with the technical regulation was obtained in March 2015 for assemblies, parts, and units of steam lines for TETs-20.

Acceptance tests, which included the study of the structure and properties of metal of pipes, bends, and butt and corner weld joints, were conducted in addition to the comparative analysis of Russian and international regulatory documents regarding the manufacture of elements of steam lines, the verification of choice of their typical sizes by a check strength calculation, and the qualification of manufacturing processes. The analysis of Russian and international regulatory documents revealed that the EN 10216-2 and ASME SA-335/SA-335M technical requirements for pipe manufacture and the EN 10222-2 requirements for the manufacture of forgings generally agree with the corresponding effective Russian standards, regulations, and specifications.

Of all the completed studies, the results of VTI investigation of the structure and properties of metal and welds of steam lines that were manufactured by FINOW for combined-cycle gas turbines at TETs-16 and TETs-20 are of the most interest. The results of this investigation are discussed below.

Pipes fabricated from P91 steel in accordance with EN 10216-2 and ASME SA-335/SA-335M were used in the construction of steam lines for the units installed at TETs-16 and TETs-20. According to the certification data of pipe suppliers, all manufactured articles used in the construction of steam lines for TETs-16 and TETs-20 met the requirements specified in international standards. Pipes of the following typical sizes (mm) were chosen to be used in the construction of the major steam lines of combined-cycle gas turbines at TETs-16 and TETs-20:

LS lines	355.6 × 40.0, 323.9 × 37.7
HRH lines	508.0 × 17.5, 457.0 × 16.0, 610.0 × 22.0

Metal cut from the main elements of steam lines (pipes, bends, and welds) was studied.

MATERIAL UNDER STUDY

P91 steel is a heat-resistant martensitic steel with approximately 9% chromium. Molybdenum, vanadium, and niobium are the primary alloying elements. These components and special regimes of heat treatment form a structure comprised of tempered martensite; $M_{23}C_6$, M_7C_3, NbC, and VC carbides; and MX-type carbonitrides (Fig. 2). The precipitation of the indicated phases enables precipitation steel hardening. Pipes made from this steel are subjected to heat treatment in the following regime: austenitization at a temperature of 1060–1080°C to dissolve the majority of carbides without any significant grain growth, cooling in air to form the martensite structure, and subsequent tempering at a temperature of 750–780°C for precipitation hardening and to relieve residual stresses associated with the martensitic transformation. As a result, the required balance of strength and plastic properties is attained.

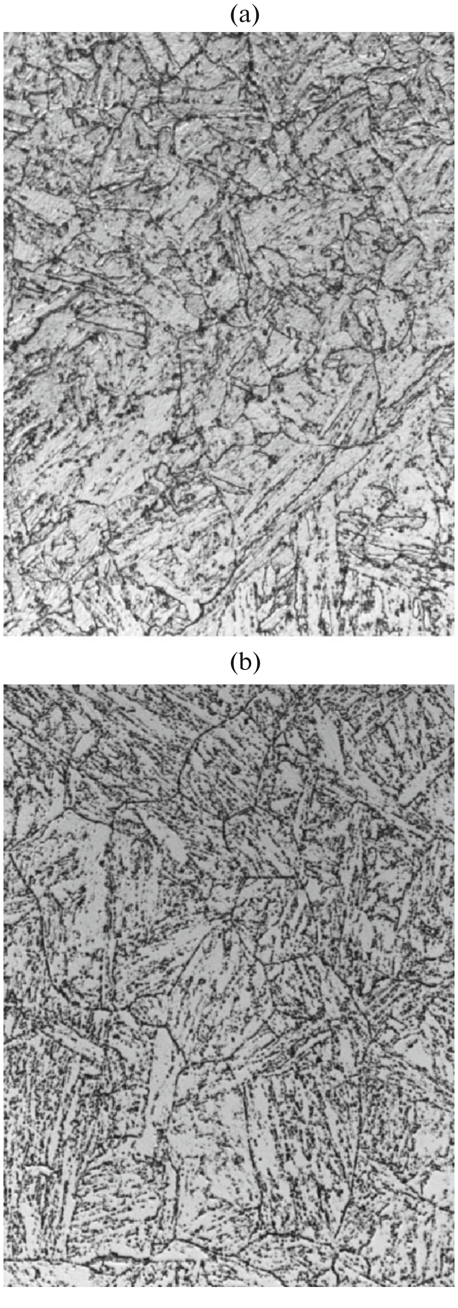

Fig. 2. Microstructure of (a) pipe and (b) bend of a live steam line (magnification ×1000).

The specific features of welding of pipe elements made from high-chromium steels are the decelerated kinetics of structural transformations and the tendency to form brittle martensite structures in the weld seam and in the near-weld area upon weld cooling (even at a relatively low rate). The temperature of martensitic transformations in these steels is 120–360°C. Therefore, the welding of such steels requires obligatory preparatory and accompanying heating and high-temperature tempering after welding [3, 4].

LS and HRH pipes were welded at the FINOW facility using the combined method in accordance with the pWPS BS 6/4/1-RNE1 procedure. The root was made by manual argon-arc welding with a filler wire with a diameter of 2.0–2.4 mm, and another 2–3 layers were then made by manual argon-arc welding to stabilize it. Groove filling was performed by manual electric-

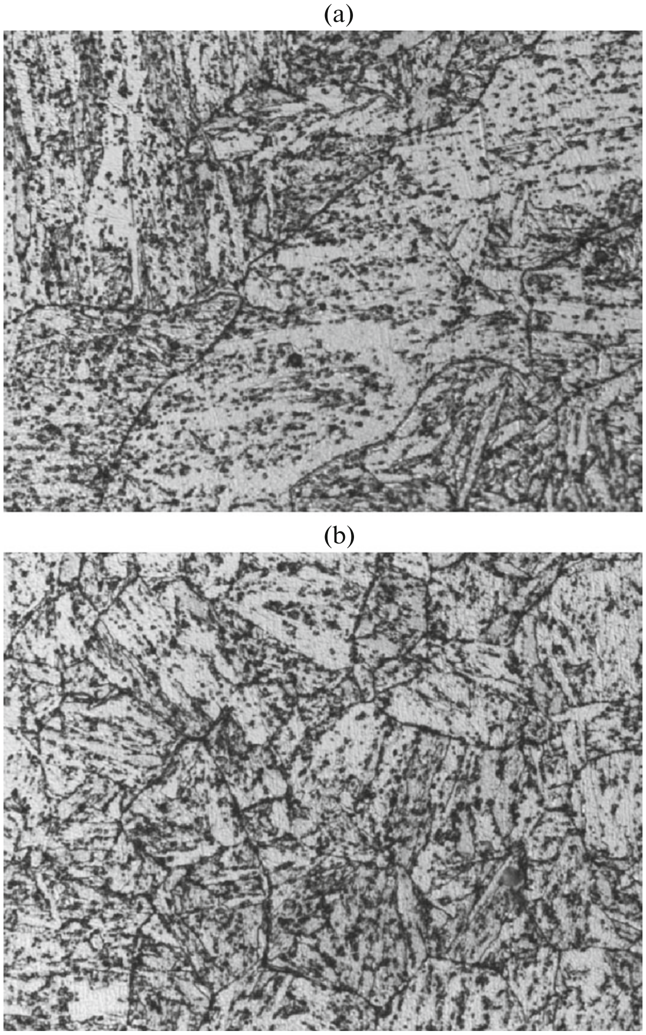

Fig. 3. Microstructure of (a) weld metal and (b) metal of the near-weld area (superheated area) in a weld joint of a live steam line manufactured from steel P91 (magnification ×1000).

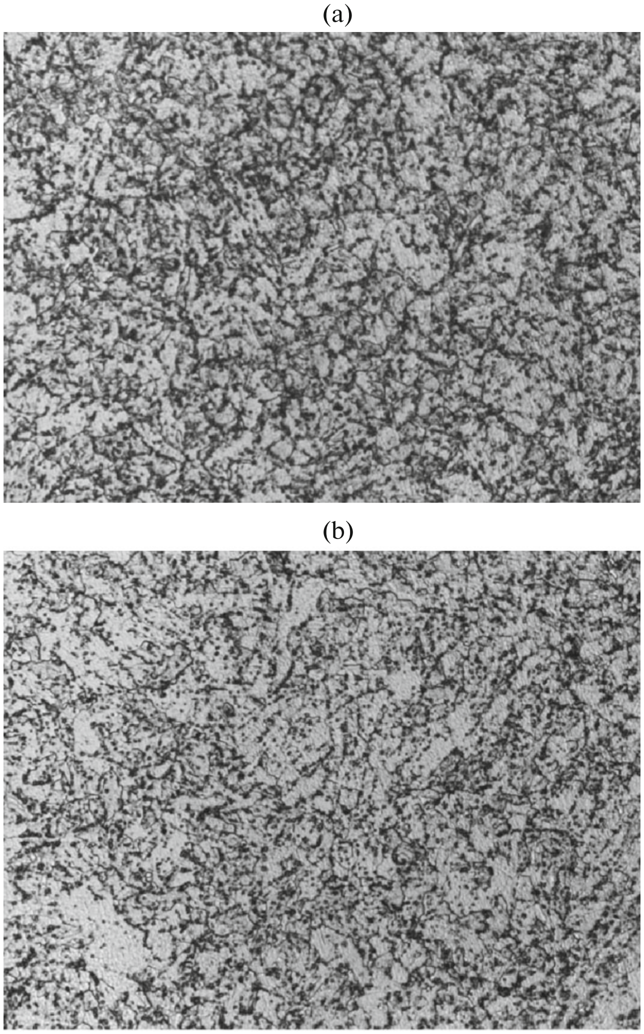

Fig. 4. Microstructure of (a) the normalization zone and (b) the intercritical heating zone in a weld joint of a live steam line manufactured from P91 steel (magnification ×1000).

arc welding with Bohler-Fox C9MV welding electrodes with diameters of 3.2 and 4.0 mm. Prior to welding, the parts were assembled with a gap of 2–4 mm using tacks and subjected to preparatory heating to 200–300°C. After welding, the welded joints were cooled to 100°C, held at this temperature for 1 h, and then subjected to high-temperature (760°C) tempering for 2–4 h.

RESEARCH TECHNIQUES AND RESULTS

Metal was studied in the test laboratory at OAO VTI with the use of equipment of the Center for Investigation of New-Generation Construction Materials for Thermal Power Engineering. This equipment was certified, in accordance with the established procedure, to be used in testing for conformance with TRCU 010/2011 and 032/2013 (accreditation certificate no. ROSS RU.001.22MX15). The tests of each specific type were conducted in accordance with the requirements set by state standards.

The microstructure of metal and welds was studied using a Leica DMI 5000 optical microscope (with software designed for structure analysis) under a magnification of ×500 and ×1000 (see Fig. 2). The microstructure typical of welds of high-chromium steels is shown in Figs. 3 and 4. It can be seen that, after high-temperature tempering, the metal of welds made by manual arc welding has a secondary sorbite structure with its dendritic orientation preserved (see Fig. 3a). The heat-affected zone in the weld joint is no larger than 3 mm. It is also seen that metal has a coarse-grain bainite structure at distances as large as 0.5 mm from the weld line (see Fig. 3b).

The normalization zone (1000–1200°C) with a fine-grain secondary sorbite structure is located at a distance of 2.0–2.5 mm from the weld line (see Fig. 4a). A zone in which the metal structure was subjected to intercritical heating is located between the normalization zone and the base metal (see Fig. 4b). This zone is characterized by a reduced strength, the hardness in it may reach 170 HV, and its structure is basically a ferrite matrix with large carbide precipitates [4].

The mechanical properties of metal were studied at room and elevated temperatures using an Instron 5982 tensile testing machine that is fitted with a system for automatic diagram recording. Figure 5 shows the results of tensile tests of metal of pipes and bends in the temperature interval from room temperature to the operating one. It can be seen that ultimate strength σ_u and yield point $\sigma_{0.2}$ of metal of pipes and bends of LS and HRH lines are roughly equal. It also follows from Fig. 5b that the yield point of metal of the studied elements satisfies the requirements of EN 10216-2 in the entire temperature interval. It should be noted that the strength properties of metal of LS pipes and bends are superior to the corresponding characteristics of metal of HRH pipes and, most especially, bends. The probable reason for this lies in the specifics of the technique of fabrication of large-diameter seamless pipes with thin walls.

The mechanical properties of welds were determined at room (20°C) and operating (570°C) temperatures. The results of tests of welds of LS lines showed that these pipelines have fine strength properties and satisfy the requirements of EN 13480. The samples were generally fractured along the heat-affected zone at the interface with the base metal, where failure strain was localized notably. This explains the fact that the level of plastic properties was lowered somewhat and confirms the above assumption that the strength and plastic properties of a weld joint as a whole are governed by the properties of its softening zone.

The resistance of metal and welds of steam lines to brittle fracture was estimated based on the results of impact-bending tests of standard samples with a notch (Charpy impact tests). The notch in weld samples ran along the weld metal.

The tests were performed using an Instron 450MPX impact tester at temperatures ranging from –40 to +60°C. The temperature of metal transition from the ductile state to the brittle one, which corresponded to a ductile fraction of 50% in the fracture, was used as the measure of resistance of metal and welds to brittle fracture [5]. The results of impact-bending tests of metal of pipes and bends of steam lines showed that critical brittleness temperature t_c is definitely negative, $t_c = -23$ and –8°C, for pipes and bends of LS lines, respectively, and $t_c = -13$ and –33°C for pipes and bends of HRH lines, respectively. This suggests that the metal of pipelines is not prone to brittle fracture. It was also found that the critical brittleness temperature of weld metal of LS lines $t_c = +5$°C, while that of HRH lines is +15°C. This is indicative of a reasonable resistance of weld joints to brittle fracture.

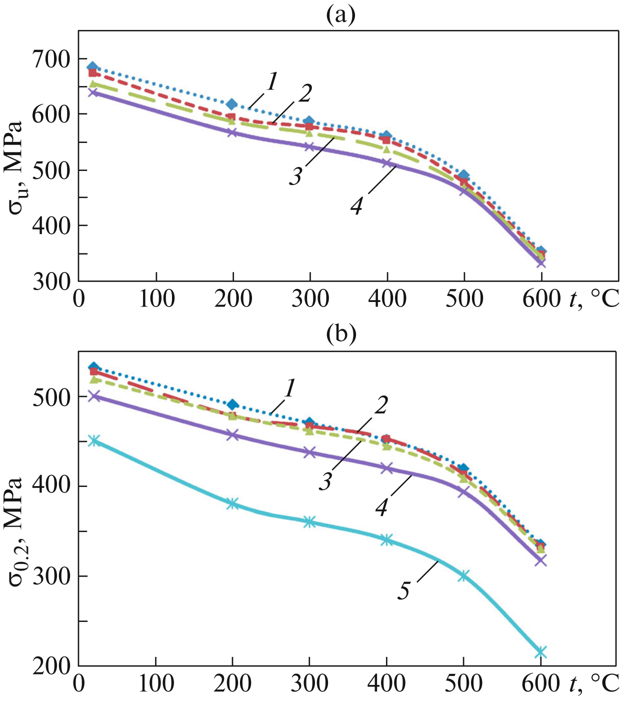

Fig. 5. Temperature dependences of (a) the ultimate strength and (b) the yield point of metal of LS pipes (*1*), LS bends (*2*), HRH pipes (*3*), and HRH bends (*4*). Curve *5* represents the requirements specified by EN 10216-2.

The hardness of metal of pipes and bends was determined using the Brinell method with an Affri Integral 5 universal automatic hardness tester. The averaged values of metal hardness for LS and HRH lines stay within the interval of 210–214 HB.

The consistency of mechanical properties of weld joints was evaluated by hardness measurements with a Wolpert-Wilson 450SVD Vickers hardness tester. The measurements were performed in various zones of a weld joint. The results of hardness measurements at different points (with distance *L* between them) located in the cross section of a joint along the median line of the pipe wall thickness are shown in Fig. 6. In the case of LS lines, the weld metal hardness is 252–265 HV, the hardness at the weld junction is 270–281 HV, and the hardness in the heat-affected zone near the base metal (in the intercritical heating zone) is 207–216 HV, while the base metal hardness is 220–230 HV.

The hardness values for welds of HRH lines were somewhat higher in general (Fig. 7). For example, the hardness of weld metal of HRH lines is close to 280 HV and the hardness at the weld junction is close to 300 HV, while the base metal hardness is roughly equal to that of LS lines. The reduction in hardness in the intercritical heating zone is also quantitatively and qualitatively similar to that in LS lines.

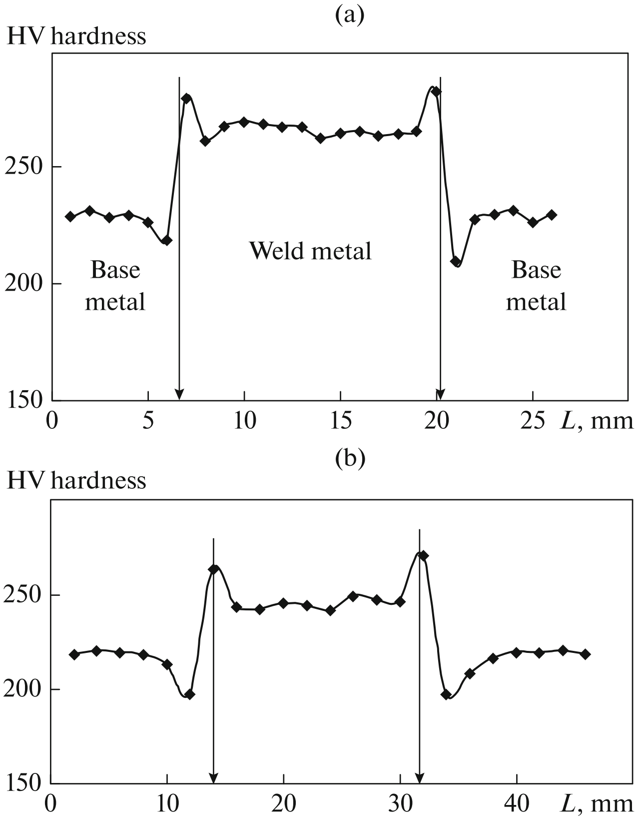

Fig. 6. Distribution of hardness in a weld joint of (a) LS lines and (b) HRH lines.

The distribution of hardness in the heat-affected zone was studied in more detail using an AFFRIDM8B automatic hardness tester. The maximum hardness (300 HV) was found in the near-weld area (superheated area; see Fig. 7). As the heating temperature in the welding process is reduced, the hardness in the heat-affected zone goes down smoothly to 260–280 HV in the normalization zone. The region adjacent to the base metal and subjected to intercritical heating during welding is the anomalous zone. A hardness of 206 HV was observed in this region.

The stress-rupture tests of metal of pipes, bends, and welds of LS and HRH lines were carried out using ATS-2230-CC-230 (Applied Test Systems, Unites States) testing machines and cylindrical samples with a working part diameter of 10 mm and a length of 200 mm. The metal of pipes and bends was tested at temperature $t = 580–660°C$ and stress $\sigma = 80–180$ MPa, and the metal of weld joints was tested at $t = 605–680°C$ and $\sigma = 65–140$ MPa. These temperature and stress values were chosen with the intention to keep the fracture pattern of the samples similar to service fracture. The point of fracture of samples with welds was generally located at the weld metal or in the heat-affected zone.

The results of tests of metal of pipes and bends of steam lines are shown in Fig. 8 in the form of dependence $\log\sigma = f(P)$, where $P = T(\log\tau - 2\log T + 36) \times 10^{-3}$ is the elevated-temperature strength parameter, T is temperature (K), and τ is time (h). It follows from the presented plots that the experimental data on long-term strength of the studied metal stay within the permissible [6] scatter band interval (20% of the average values of this parameter specified by European standard EN 10216-2). The long-term strength of metal of pipes of LS lines almost matches the requirements specified in EN 10216-2 (see Fig. 8a), while certain experimental values of long-term strength of metal cut from pipes of HRH lines and bends of LS and HRH lines lie below (within a 20-percent deviation from) the corresponding values specified in European standards (see Figs. 8b–8d). The results of tests of weld joints of steam lines for long-term strength are presented in Fig. 9. The extrapolation of the obtained test results to 200000 h ($P = 29.9$) at an operating temperature of 570°C revealed that $\sigma = 90$ MPa for weld joints of LS lines and $\sigma = 75$ MPa for weld joints of HRH lines.

It can be seen that the experimental points are located within a relatively narrow scatter band. Low values of stress rupture ductility were derived from the experimental data for certain samples. For example, percentage elongation δ of a sample tested under a stress of 90 MPa at a temperature of 638°C is at the level of 3.0%, which is indicative of an increased brittleness of welds with such properties under creep conditions. As was already noted, the point of fracture of the majority of studied samples was located in the heat-affected zone of a weld joint.

DISCUSSION

Although the data accumulated during service of thermal and mechanical TPS equipment manufactured from 9%-chromium steel in Europe, United States, China, and several other countries are reassuring, the failure of certain elements (primarily weld joints) made from this steel has also been reported [7]. It should be kept in mind that, while the considered martensitic steel has a high elevated-temperature strength, it is less workable than pearlite steels. Therefore, more stringent requirements are imposed on the regime of heat treatment and technological processing (welding). Since the data on long-term usage of Russian-manufactured pieces of equipment made from chromium steels are lacking, the presented results of studies of samples of P91 steel cut from steam lines manufactured by FINOW provide valuable information regarding the reliability and long-term performance of advanced equipment. The research conducted at OAO VTI extends beyond the limits of typical certification tests; the issues of inspection and the criteria of operational reliability of elements made from chromium steels will be discussed in a separate paper. The analysis below should help estimate the appropriateness and efficiency (i.e., relevance) of cer-

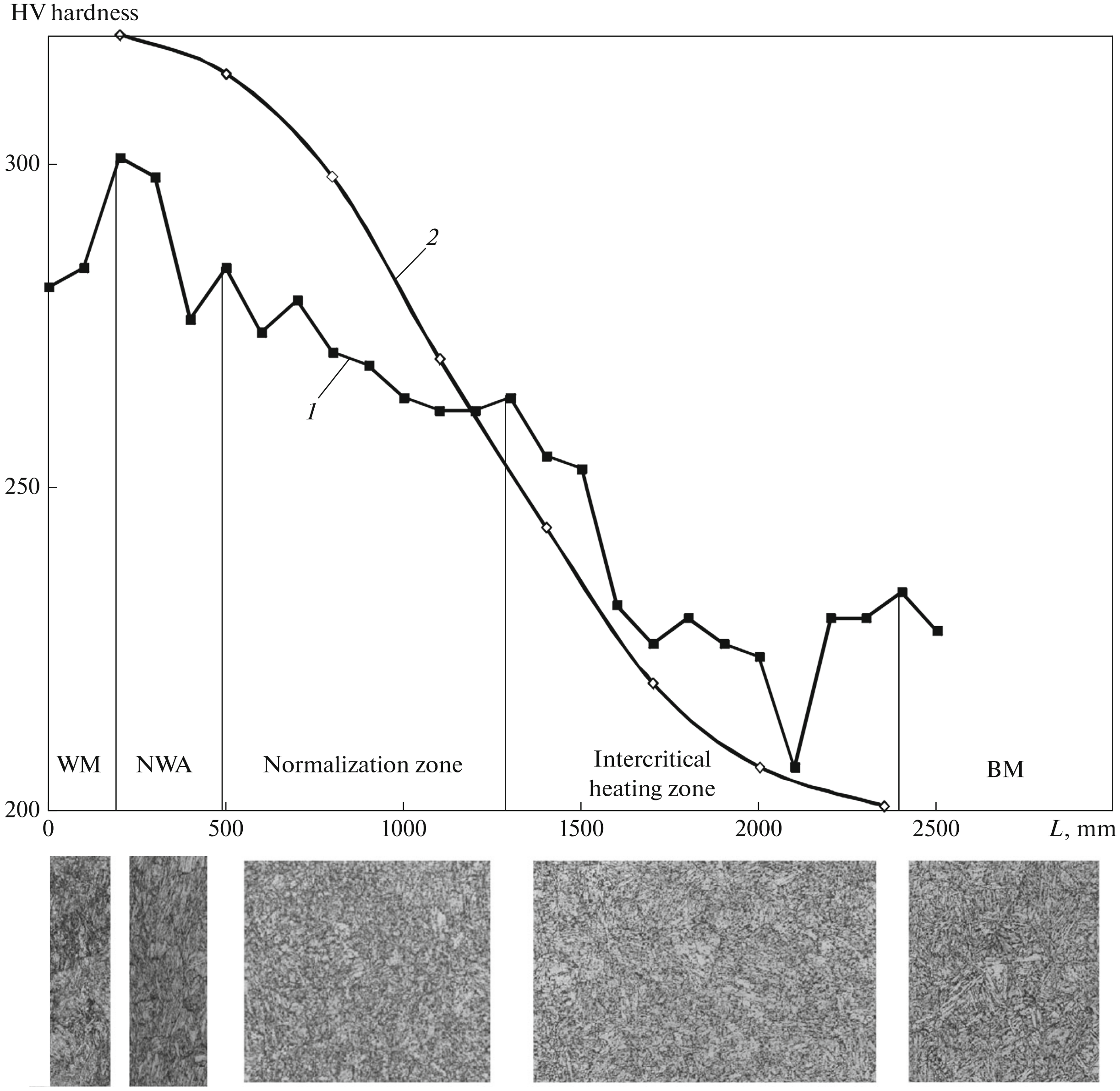

Fig. 7. Microstructure and distribution of microhardness in a weld joint of an HRH line manufactured from P91 steel. Curves *1* and *2* represent the weld thermal cycle and the distribution of microhardness. WM is the weld metal, NWA is the near-weld area (superheated area at a temperature of 1250–1350°C), and BM is the base metal.

tification tests of new equipment made from chromium steels (including Russian steels of this type).

The averaged results of tests on the determination of short-term mechanical properties of metal of pipes and bends of LS and HRH lines are listed in the table. The values specified by the EN 10216-2 standard and Russian technical regulations [6] are also listed for comparison. It can be seen that the strength and plastic properties of the studied metal at room temperature satisfy the requirements of EN 10216-2 and [6] (the former requirements are more stringent with regard to the strength properties). As was already noted, the mechanical properties of the tested weld joints also satisfy the regulatory requirements. As for the results of impact-bending tests, the obtained values of impact strength of metal and weld joints are fairly high. This effectively guarantees a decent resistance to brittle fracture on the basis of the ductile-to-brittle transition temperature criterion: t_c is negative for the base metal and does not exceed +15°C for welds.

The investigation of the distribution of metal hardness in weld joints of steam lines showed that a region subjected to intercritical heating during welding is present in the transition zone. The hardness in this region (soft interlayer) is reduced considerably, thus leading to the localization of local deformations and a

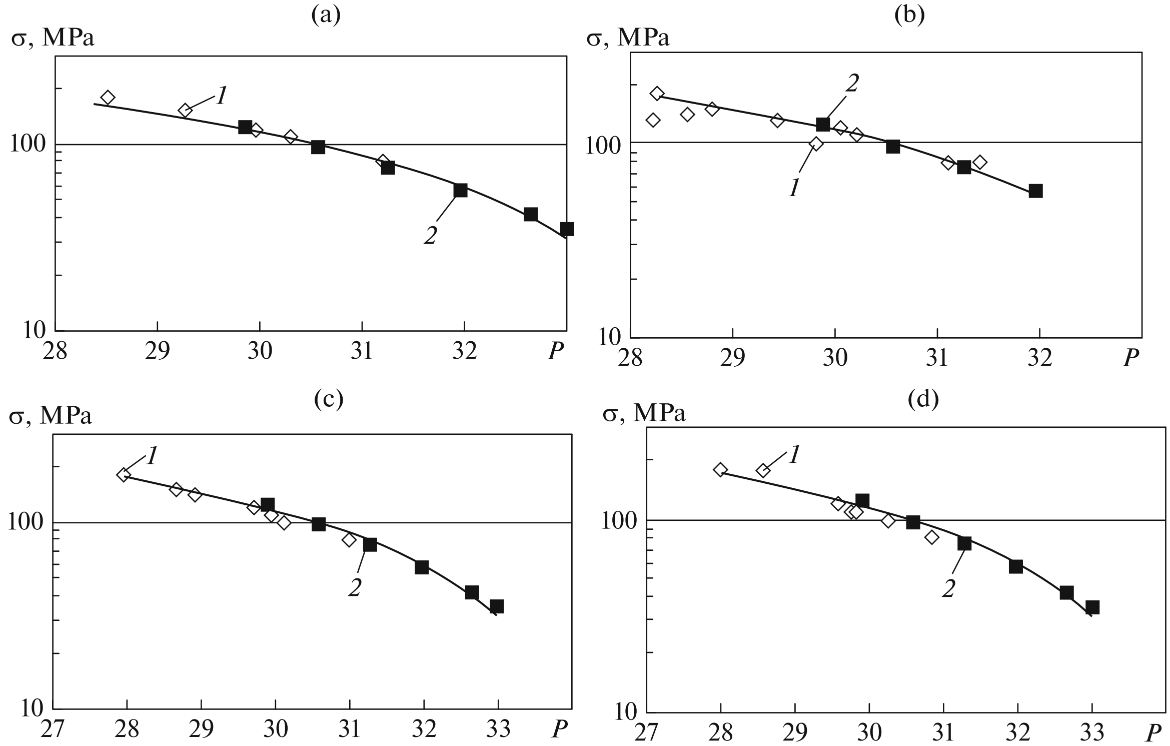

Fig. 8. Experimental (*1*) and required (EN 10216-2; *2*) values of long-term strength of metal of (a) pipes and (b) bends of LS lines and (c) pipes and (d) bends of HRH lines.

reduction in the overall weld strength. This is confirmed by the results of metallographic examination of samples that were ruptured during stress-rupture tests. Figure 10 shows that the sample was ruptured after stress-rupture tests along the intercritical heating zone near the base metal, where the structure has the form of a ferrite matrix with a globular carbide phase. The hardness reaches its minimum of 206–211 HV here, while the hardness of the base pipe metal is 220 HV, and that of the weld metal and the metal at the weld line is 250–280 HV.

It can also be seen (see Fig. 10) that the rupture is of an intergranular nature and is initiated by the formation of micropores at grain boundaries. These pores fuse into microcracks, and these grow and turn into a macrocrack. The indicated features of the process kinetics define the mechanisms of propagation of fracture in the considered zone under creep conditions and govern the long-term strength of a weld joint in general. The same specific features define the characteristics of stress rupture ductility of weld samples. While the stress rupture ductility of metal of pipes and bends falls within the interval of 10–20%, the interval for weld joints is much wider and has its lower boundary at the level of just 3%.

Long-term strength is the primary rated characteristic of metal of high-temperature pipelines. It was determined for metal and welds at an elevated-tem-

Results of tests of mechanical properties of metal at room temperature

Steel grade	Parameter				
	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	impact strength, J/cm^2	hardness, HB
X10CrMoVNb9-1	539.3–599.2	703.2–722.7	21.0–23.0	KCV 228.2–254.8	210–214
X10CrMoVNb9-1 in accordance with EN 10216-2	No less than 450	630–830	No less than 19	KCV—40 (fracture work)	–
10Kh9MFB in accordance with [3]	No less than 400	No less than 600	No less than 19	KCU—78	No more than 255

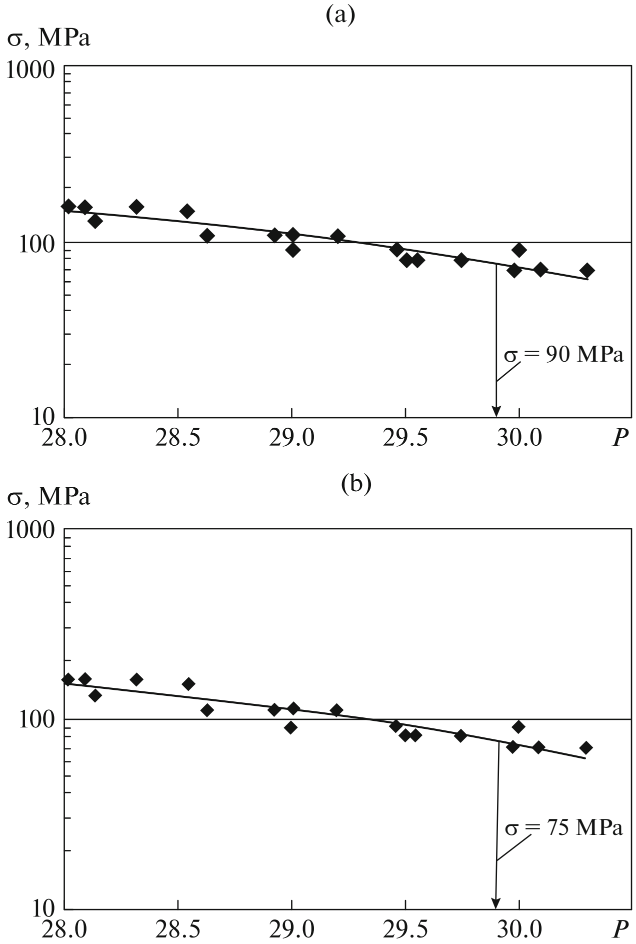

Fig. 9. Long-term strength of weld joints of (a) LS and (b) HRS lines.

perature strength value of approximately 29.9. At the given operating temperature of 570°C, this value corresponds to a service life of 200 000 h.

The long-term strength (MPa) for metal and welds (steel X10CrMoVNb9-1) were determined at an operating temperature of 570°C for a service life of 200000 h by processing the experimental data obtained in tests (see Figs. 8–9). The derived values are listed below together with the required long-term strength values specified by EN10216-2 for pipe metal.

LS pipe	127
LS bend	115
HRH pipe	112
HRH bend	112
EN 10216-2 requirements	124
Requirements in accordance with the engineering decision of OAO VTI, OAO NPO TsNIITMash, and OAO NPO TsKTI	112
LS weld	90
HRH weld	75

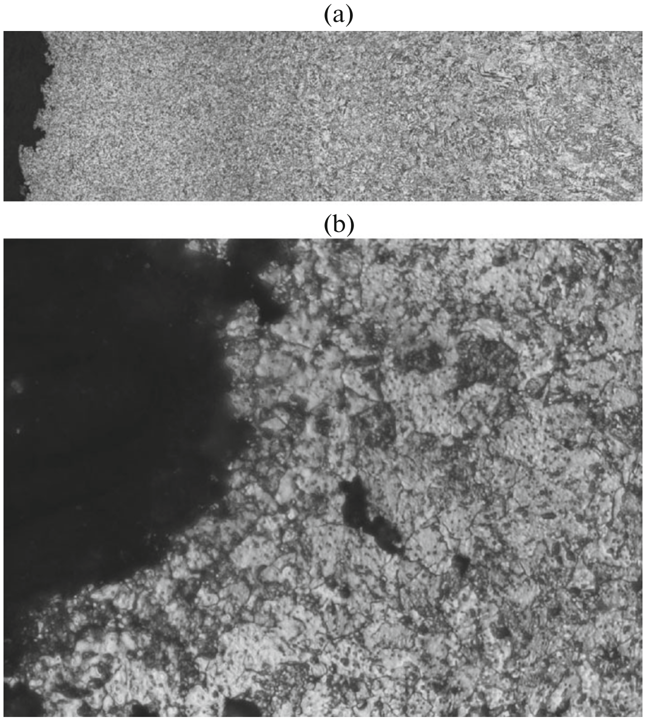

Fig. 10. (a) Panoramic image of the fracture zone (magnification ×100) and (b) fracture pattern (magnification ×1000) of a weld joint of an LS line after a 370-h-long stress-rupture test at a temperature of 649°C and a stress of 80 MPa.

It can be seen that only the metal of LS pipes fully satisfies the EN 10216-2 requirements regarding the long-term strength, while the level of long-term strength of metal of HRH pipes and bends of both steam lines (LS and HRH) is somewhat lower than that specified by European standards. The experience in pipe manufacture shows that the specifics of fabrication of large-diameter pipes with thin walls make it harder to satisfy the EN 10216-2 requirements regarding the long-term metal strength.

In 2009–2010, two of the world's leading laboratories (Electric Power Research Institute and European Creep Collaborative Committee) presented the results of tests of pipes made from P91 steel. The results showed that the actual long-term strength does not always reach the one specified in EN 10216-2. It is planned that the standard values of strength will be corrected on the basis of these studies. The results of tests of pipe metal (steels P91 and 10Kh9MFB) conducted at the leading Russian materials laboratories (OAO VTI, OAO NPO TsNIITMash, and OAO NPO TsKTI) have also confirmed that the requirements of the European standard regarding the long-term strength of P91 steel are somewhat overstated. Based on the analysis of the available experimental data, the mentioned materials research institutes have rendered a joint engineering decision on the choice of the principal rated characteristics (i.e., allowable stresses) for P91 and 10Kh9MFB steels in the operating temperature interval.

The long-term strength requirements set by this engineering decision were given above. It can be seen that the actual values long-term strength of all the studied metal samples cut from both steam lines satisfy these requirements. The indicated long-term strength values were used in check strength calculations for choosing the basic typical sizes of steam lines in the framework of the certification procedure. The results of these calculations confirmed the compliance with the strength requirements for LS and HRH lines under the given operating parameters and a service life of 200000 h.

The long-term strength of welds is much lower than that of base metal. As expected, the long-term strength of metal and of its weld are correlated to a certain extent: the lower the long-term strength of base metal is, the lower is that of its weld (under similar welding conditions).

The comparative analysis of the obtained results of stress-rupture tests of welds and the base metal showed that the strength factor of welds φ_w (the ratio of long-term strengths of a weld and the base metal) satisfies the requirements of Russian standards of strength calculation ($\varphi_w \geqslant 0.7$) [8].

CONCLUSIONS

(1) According to the results of studies, the mechanical properties of metal of pipes and bends fabricated from P91 steel generally satisfy the requirements set by European regulations and Russian technical specifications for pipes made from 9%-chromium steel.

(2) Weld joints of elements made from P91 steel have decent strength properties but a low (somewhat lower than the requirements set by EN 10216-2 for weld metal) level of plastic properties. This may be attributed to the localization of deformations in the heat-affected zone within the intercritical heating region.

(3) Metal and weld joints of elements of steam lines made from P91 steel have demonstrated fine resistance to brittle fracture. This is confirmed by the fact that the critical brittleness temperature of P91 steel and its welds is either negative (in the majority of cases) or exceeds 0°C only slightly.

(4) The long-term strength properties of P91 steel satisfy the requirements set by European regulations only in the case of pipes of LS lines, while the experimental data on long-term strength of pipes of HRH lines and bends of LS and HRH lines lie in the lower region of the specified interval. At the same time, the long-term strength of metal of the indicated elements is at the level set by the joint engineering decision of OAO VTI, OAO NPO TsNIITMash, and OAO NPO TsKTI for DI-82 and P91 steels at the given design parameters (temperature and service life).

(5) Since the long-term metal strength is the principal rated parameter for high-temperature elements, the obtained results support the notion that the certification testing of steam lines and other equipment made from 9%-chromium steels should necessarily involve the determination of elevated-temperature strength parameters of metal. It also seems advisable to perform special on-receipt inspection of elements made from these steels.

ACKNOWLEDGMENTS

This study was supported financially by the Ministry of Education and Science of the Russian Federation (unique project identifier RFMEFI 57614 X0048).

REFERENCES

1. A. V. Klimenko and E. A. Grin', Provision of thermal engineering with structural materials – basis of its safe operation and development, Therm. Eng. **61**, 41–46 (2014).
2. A. V. Dub, V. N. Skorobogatykh, and I. A. Shchenkova, New heat–resistant chromium steels for a promising objects of power engineering, Therm. Eng. **55**, 594–601 (2008).
3. G. L. Petrov, V. N. Zemzin, and F. G. Gonserovskii, *Svarka zharoprochnykh nerzhaveyushchikh stalei* (Welding of Refractory Stainless Steels), (Mashizdat, Moscow, 1963).
4. A. E. Anokhov and P. M. Korol'kov, *Svarka i termicheskaya obrabotka v energetike* (Welding and Thermal Treatment in Energetics), (Ekotekhnologiya, Kiev, 2006).
5. *PNAE G-7-002-86. Normy rascheta na prochnost' oborudovaniya i truboprovodov atomnykh energeticheskikh ustanovok* (Norms of Calculation of Equipment and Pipelines of Atomic Power Plants on Strength), (Energoatomizdat, Moscow, 1989).
6. *TU 14-3R-55-2001. Truby stal'nye besshovnye dlya parovykh kotlov i truboprovodov* (Steel Sutureless Tubes for Steam Boilers and Pipelines), (GNTs RF TsNIITmash, Moscow, 2001).
7. M. Boder, J. R. Thumer, and K. Glassenap, 9%-chromium steel P91 and P92 in german power plants – from 1991 to the present day, VGB Power Tech., No. 7, 51–58 (2013).
8. *RD-10-249-98. Normy rascheta na prochnost' statsionarnykh kotlov i truboprovodov para i goryachei vody* (Norms of Calculation of Stationary Boilers and Pipelines for Steam and Hot Water on Strength), (Gosgortekhnadzor Rossii, Moscow, 1999).

Translated by D. Safin