Archives of Materials Science and Engineering

Volume 58
Issue 1
November 2012
Pages 5-12

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Material properties and structure of thick-walled elements made of steel 7CrMoVTiB10-10 after long-term annealing

A. Zieliński*, J. Dobrzański
Institute for Ferrous Metallurgy, ul. K. Miarki 12, 44-100 Gliwice, Poland
* Corresponding e-mail address: azielinski@imz.pl

Received 16.09.2012; published in revised form 01.11.2012

ABSTRACT

Purpose: Condition assessment of material and welded joints with regard to required utility properties of low-alloy steel for operation at elevated temperature.

Design/methodology/approach: The structural and mechanical testing of parent material and welded joint at room and elevated temperature after annealing at 550°C and 600°C for 30,000 h was carried out.

Findings: The effect of temperature and duration of long-term annealing on mechanical properties, hardness and structure of tested material and welded joint was determined.

Practical implications: The presented method can be used for evaluation and qualification of structural changes in power station boiler components operating in creep conditions.

Originality/value: The presented results of changes in the mechanical properties, structure and in the precipitation processes are applied to evaluation the condition of the elements in further industrial service.

Keywords: Structure; Degradation; Hardness; Creep; Steel T24

Reference to this paper should be given in the following way:

A. Zieliński, J. Dobrzański, Material properties and structure of thick-walled elements made of steel 7CrMoVTiB10-10 after long-term annealing, Archives of Materials Science and Engineering 58/1 (2012) 5-12.

MATERIALS

1. Introduction

Boilers with supercritical working parameters at the required low level of emission of harmful substances into the atmosphere demand higher and higher discharge parameters of steam. The increase in these parameters requires the quest for and use of new materials with higher and higher mechanical parameters and more and more complex manufacturing process for making the components of boiler pressure section out of them. Among the critical boiler pressure section components the membrane walls whose materials can be operates at up to approx. 550°C in systems with supercritical parameters, including new bainitic steels for components of the membrane walls and collector pipes, should be distinguished [1-5]. For these components the new-generation low-alloy steel of 2.25%Cr-1%Mo type with micro-additives in 7CrMoVTiB10-10 (P24) grade has been developed and used [2-4,6]. The steel is the result of extensive research, to a large extent conducted under the European structures of COST 511, 522 and 536, where welding materials and technologies for manufacturing boiler components out of them were being developed [2,5,6]. For the materials of manufactured boiler components the characteristics of material and welded joints are created to acquire knowledge on their behaviour under the operating conditions [7-19]. Due to the specific operating nature of the materials, the construction of these characteristics and revealing of degradation and destruction processes that occur in them are a long-term operation and covers approx. 15 to 20 years.

Below, there are results of testing the parent material and homogeneous welded joint made under large manufacturer conditions [13-16]. The mechanical properties and effect of long-term annealing on the properties and structure of material and joint at a temperature similar to the operating one were compared and fitness of tested material for manufacturing of pressure section components of boilers for supercritical parameters with regard to the established requirements was assessed.

2. Research material

The research material was a section of the pipe from industrial heat, after the required normalising and tempering, delivered by Vallourec & Mannesmann under the international cooperation in COST programme, which was made of low-alloy chromium steel with molybdenum and micro-additives in 7CrMoVTiB10-10 grade. The circumferential welded joint was made using the welding materials and technology agreed with Thyssen Welding under the above-mentioned cooperation.

The comprehensive NDTs were carried out on the material of collector pipe and homogeneous circumferential welded joint. Tests aimed at the assessment of properties and structure as well as behaviour of material and welded joint under the operating conditions, in particular determination of the effect of temperature, loading and time on the set of utility properties, are carried out on the material prepared like that in the Institute for Ferrous Metallurgy. Chemical composition of the steel tested with regard to the requirements of standard is presented in Table 1.

3. Research scope

As a part of the tests, the properties of tested material were determined. In the assessment of material condition and the level of required utility properties of low-alloy steel for operation at elevated temperature, the examination of the effect of temperature and duration of long-term annealing on mechanical properties, hardness and structure of tested material and welded joint were assumed to be particularly important.

The selected results of examinations obtained so far and the assessment of properties of the new low-alloy bainitic steel in 7CrMoVTiB10-10 (P24) grade are presented below.

4. Research results

4.1. Effect of long-term annealing on mechanical properties of 7CrMoVTiB10-10 steel and welded joint

The comparison of the obtained test results for the following: tensile strength TS, yield point at room temperature YP and at 500°C YP^{500}, elongation A_5 in tensile test at room temperature and impact energy at room temperature KV, for the parent material and homogeneous circumferential welded joint made of the tested steel in initial state and after long-term annealing for 1,000, 5,000, 10,000 and 30,000 hours at 550°C are presented in Figs. 1-5 and at 600°C - in Figs. 6-10.

These tests show that both the parent material and the homogeneous circumferential welded joint made of 7CrMoVTiB10-10 steel reveal a systematic decrease in tensile strength and yield point at both room temperature and elevated temperature, similar to the expected working temperature, as duration of annealing increases up to 30,000 hours. After long-term annealing at 550°C tensile strength TS was reduced insignificantly, i.e. from approx. 605 MPa in initial state to approx. 590 MPa after 30,0000 hours, and it is still higher than the minimum required value of 565 MPa for pipes in initial state, whereas after long-term annealing at 550°C tensile strength TS was reduced significantly, i.e. from approx. 605 MPa in initial state to approx. 530 MPa after 30,0000 hours, and it was lower than that required for pipes in initial state already after 10,000 hours.

Similarly, yield point was reduced, both at room temperature and at 500°C too, as follows: after annealing at 550°C yield point YP was reduced from approx. 515 MPa in initial state to approx. 490 MPa after 30,000 hours and it was higher than the minimum value required for pipes in initial state and after annealing at 600°C yield point YP was reduced from approx. 515 MPa in initial state to approx. 425 MPa after 30,000 hours and only after this time of annealing it was lower than the minimum value required for pipes in initial state, whereas yield point YP500 after annealing at 550°C was reduced from approx. 400 MPa in initial state to approx. 340 MPa after 30,000 hours and it was higher than the minimum required value of 324 MPa and after annealing at 600°C it was reduced to approx. 270 MPa after 30,000 hours and it was lower than the minimum required value already after 10,000 hours of annealing.

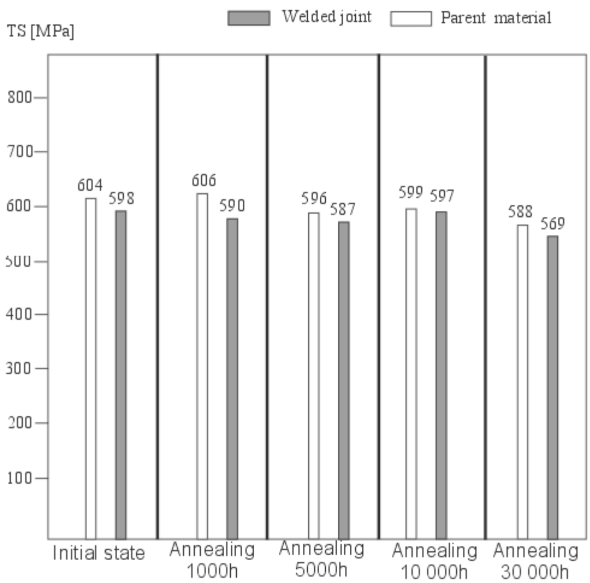


Fig. 1. Tensile strength of parent material and welded joint in initial state and after annealing at 550°C

Table 1.
Chemical composition of material of tested pipe made of steel 7CrMoVTiB10-10

	Chemical composition [%]											
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V	B
Check analysis	0.09	0.24	0.53	0.015	0.002	2.51	1.01	0.015	0.08	0.24	0.007	0.005
to PN- EN 10216-2	0.05 0.10	0.15 0.45	0.30 0.70	- 0.02	- 0.01	2.20 2.60	0.90 1.10	- 0.02	0.05 0.10	0.20 0.30	- 0.010	0.0015 0.0070

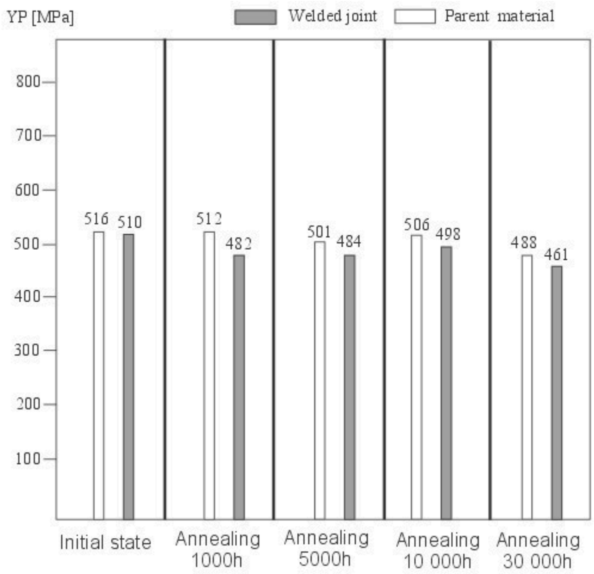


Fig. 2. Yield point of parent material and welded joint in initial state and after annealing at 550°C

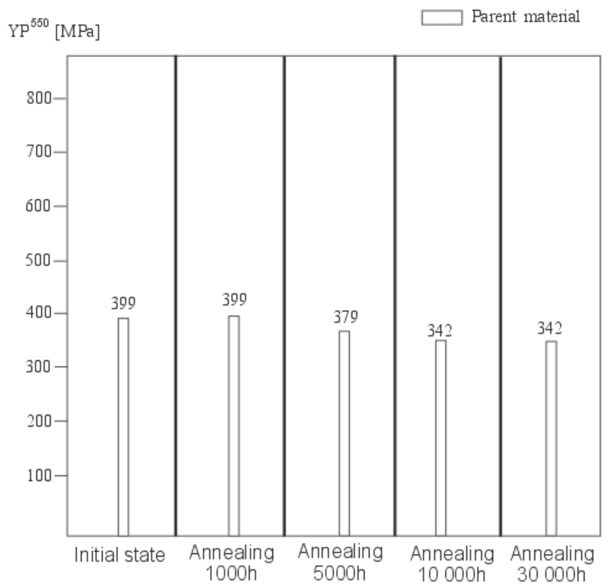


Fig. 4. Yield point at elevated temperature YP of parent material and welded joint in initial state and after annealing at 550°C

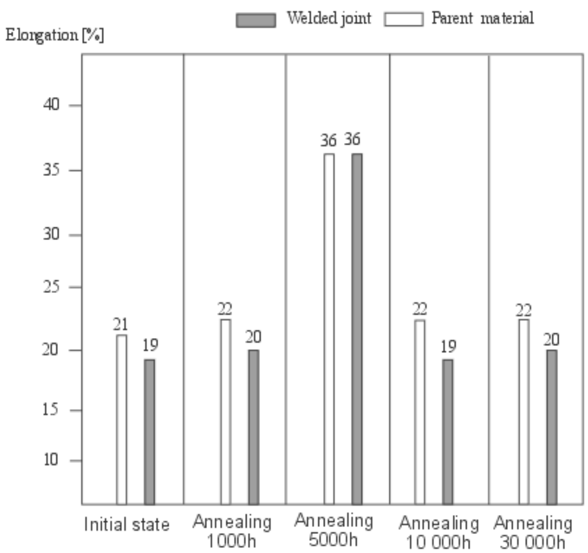


Fig. 3. Elongation A_5 of parent material and welded joint in initial state and after annealing at 550°C

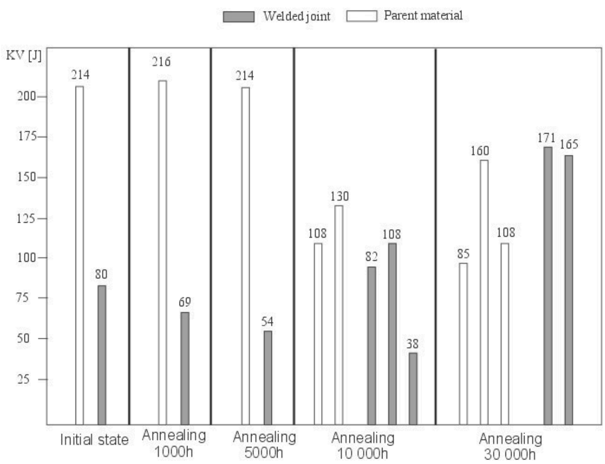


Fig. 5. Impact resistance of parent material and welded joint in initial state and after annealing at 550°C

Plastic properties, the measure of which is elongation in tensile test and impact energy in impact test, for both the test temperatures are significantly higher than those required for material in initial state and amount to after annealing for 30,000 hours, respectively: elongation - 22 and 28% and impact energy on KV samples - approx. 120 and approx. 220 J.

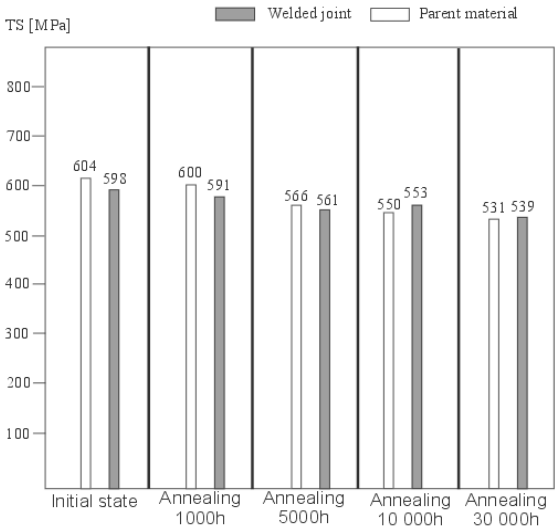


Fig. 6. Tensile strength of parent material and welded joint in initial state and after annealing at 600°C

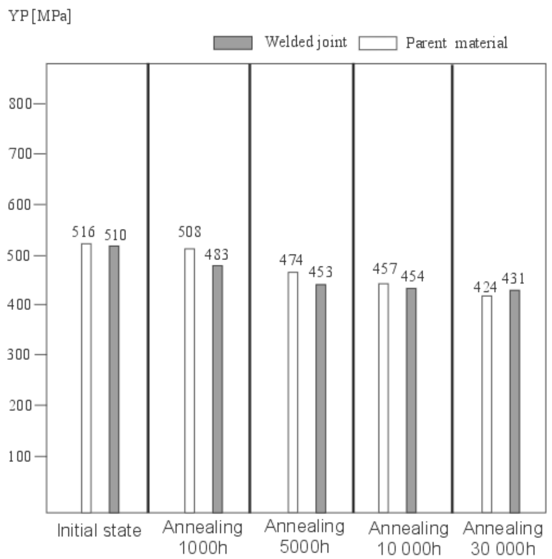


Fig. 7. Yield point of parent material and welded joint in initial state and after annealing at 600°C

The reduction in hardness HV10 was also observed, which was insignificant after annealing at 550°C, i.e. from approx. 205 HV10 in initial state to approx. 190 HV10 after 30,000 hours, and significant after annealing at 600°C, i.e. to approx. 180 HV10 after 30,000 hours (Fig. 11). These changes correlate with changes in mechanical properties as described above and changes in structure of tested steel as described below.

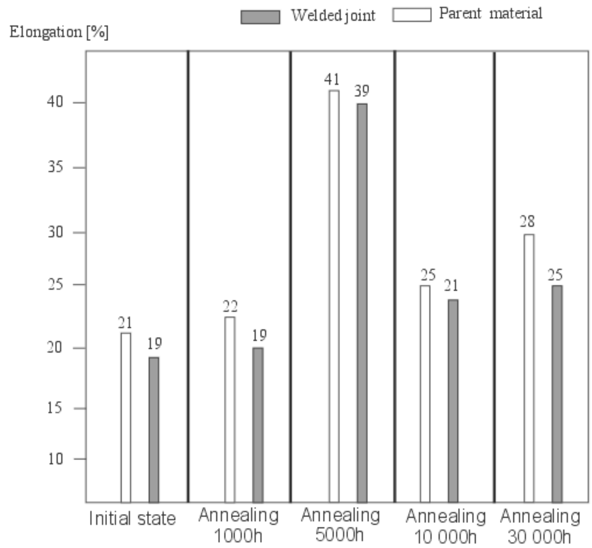


Fig. 8. Elongation A_5 of parent material and welded joint in initial state and after annealing at 600°C

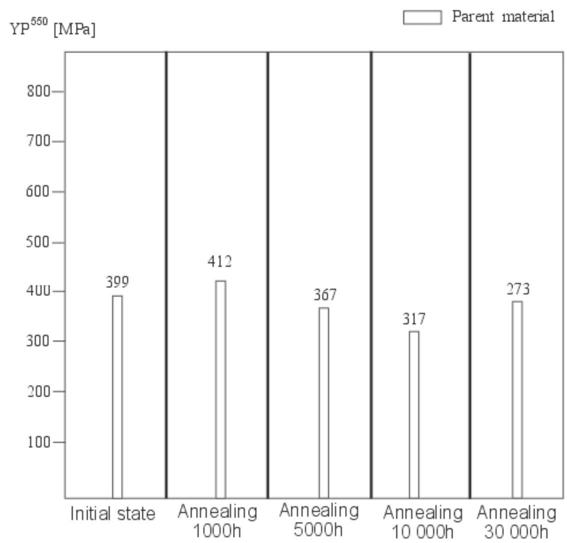


Fig. 9. Yield point at elevated temperature YP of parent material and welded joint in initial state and after annealing at 600°C

The investigations of changes in mechanical properties of homogeneous circumferential welded joint made of 7CrMoVTiB10-10 steel with regard to their nature do not differ from that found for the parent material of pipe. However, it needs to pay attention that only after annealing at 600°C tensile strength TS is lower than the minimum one required for pipes made of the tested steel in initial state already after 5,000 hours, whereas after 30,000 it is reduced to approx. 540 MPa. In other cases, mechanical properties are higher than the required minimum value for pipes in as-received state even after annealing for 30,000 hours.

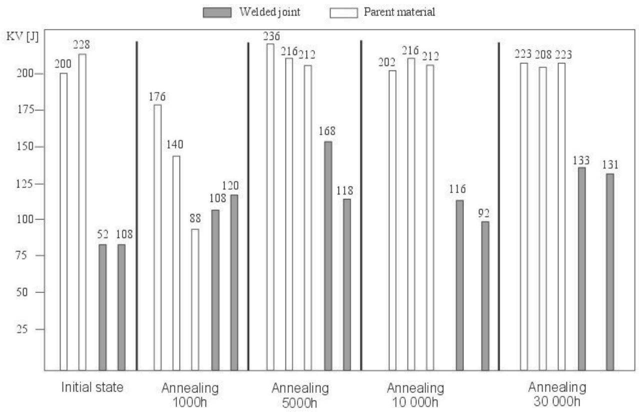


Fig. 10. Impact resistance of parent material and welded joint in initial state and after annealing at 600°C

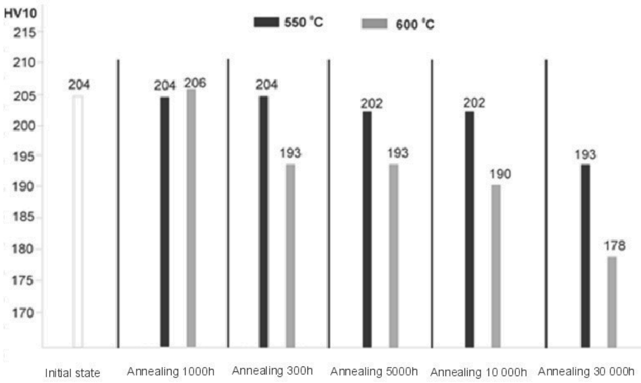


Fig. 11. Effect of long-term annealing at 550 and 600°C on hardness HV10 of 7CrMoVTiB10-10 steel

Elongation in tensile test, even after annealing at both levels of test temperature for 30,000 hours, is higher than the minimum value for pipes in initial state. Also, impact energy on KV samples in weld material of the welded joint is higher or significantly higher than the required minimum value for parent material of tested pipes and depends on test duration and temperature.

The hardness tests of heat-affected zone and weld metal of the tested circumferential welded joint revealed its systematic reduction. Hardness HV10 of heat-affected zone after annealing at 550°C was reduced from approx. 240 HV10 in initial state to 190 HV10 after 30,000 hours and after annealing at 600°C - to approx. 185 HV10 after 30,000 hours (Fig. 12), whereas hardness HV10 of weld metal after annealing at 550°C was reduced from approx. 280 HV10 in initial state to approx. 200 HV10 after 30,000 hours and after annealing at 600°C - to approx. 205 HV10 after 30,000 hours (Fig. 12). These changes correlate with changes in structure of tested steel and elements of circumferential welded joint described in the further part of this study.

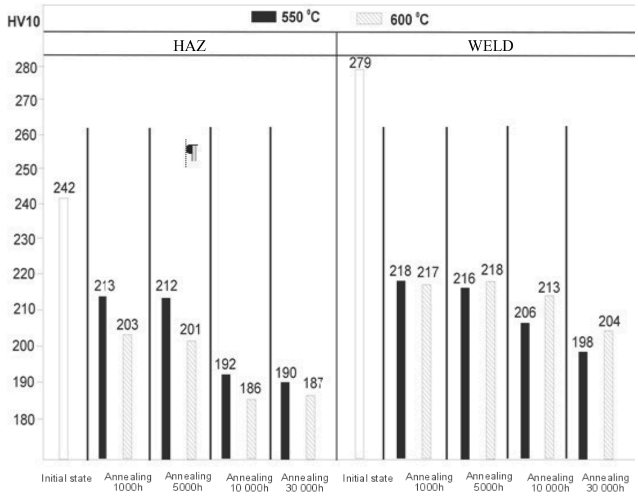


Fig. 12. Effect of long-term annealing at 550 and 600°C on hardness HV10 of heat-affected zone and weld metal of circumferential welded joint made of 7CrMoVTiB10-10 steel

4.2. Effect of long-term annealing on structure of 7CrMoVTiB10-10 steel and homogeneous circumferential welded joint

The 7CrMoVTiB10-10 steel pipe selected for testing is characterised by the structure which is the mixture of lower bainite with martensite and very fine carbide precipitations, mainly at primary austenite grain boundaries and within the bainite areas, with hardness of approx. 205 HV10 (Fig. 13).

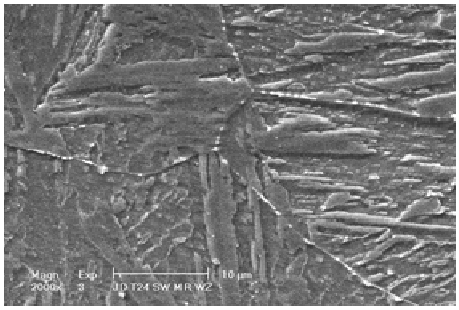


Fig. 13. Image of structure observed under scanning electron microscope, selected for testing of pipe made of low-alloy bainitic steel 7CrMoVTiB10-10 (mag. 2000x)

The investigations of structure under scanning electron microscope with magnifications of up to 5,000x showed that annealing for up to 30,000 hours had resulted in changes in the image of observed structure as compared to structure in initial state, but it is still represented by lower bainite with martensite. The increase in amount and size of carbide precipitations inside grains, at the boundaries of sub-grains that are being formed and at the boundaries of primary austenite grains is visible. Long-term exposure to elevated temperature revealed decay of laths in bainite/martensite areas with simultaneous occurrence of sub-grains and carbides inside them and at their boundaries and carbides at boundaries of primary austenite grain, which form chains in places, and the decay was insignificant after annealing at 550°C and insignificant and locally partial after annealing at 600°C.

a)

b)

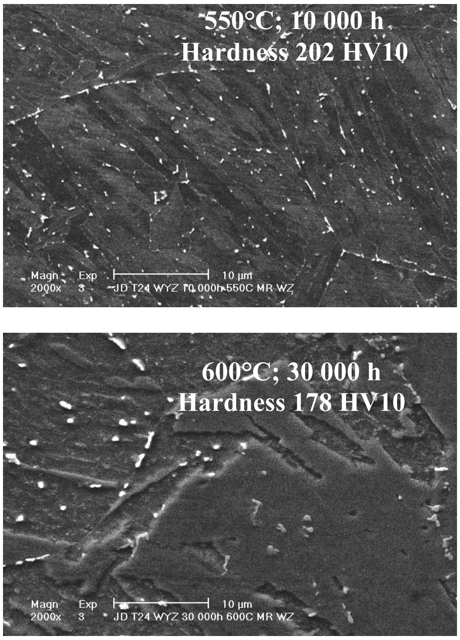


Fig. 14. Structure of 7CrMoVTiB10-10 steel after long-term annealing at elevated temperature, observed under scanning electron microscope (mag. 2000x): a) at 550°C after 10,000 hours, b) at 600°C after 30,000 hours

Thus, long-term annealing at elevated temperature for up to 30,000 hours did not result in significant changes in the form of bainite and martensite, although the plate decay process with simultaneous occurrence of sub-grains was initiated, particularly after annealing at 600°C. The result of extending the duration of annealing is the intensification of carbide precipitation processes. The intensification of these processes, after the same time of annealing, is significantly higher after annealing at 600°C. Changes in structure of tested 7CrMoVTiB10-10 steel caused the reduction in mechanical properties of welded joint material, at the same time resulting in increase in their plastic properties (Elongation, KV) in some cases. These changes also resulted in reduction in hardness from approx. 205 HV10 in initial state to approx. 190 HV10 after annealing at 550°C and to approx. 180 HV10 after annealing at 600°C for 30,000 hours.

The examples of structure images that illustrate changes being the effect of exposure to certain temperatures in time, obtained as a result of examinations of 7CrMoVTiB10-10 steel after long-term annealing for 10,000 and 30,000 hours carried out under scanning electron microscope, are presented in Fig. 14.

The structure of heat-affected zone and weld metal in initial state is a little bit diverse and depends on the place of examination, which is the effect of welding process resulting from used technology and having kept its parameters on required level. The typical structure is the mixture of bainite in different forms and martensite with small amount of ferrite (Figs. 15 and 16).

a)

b)

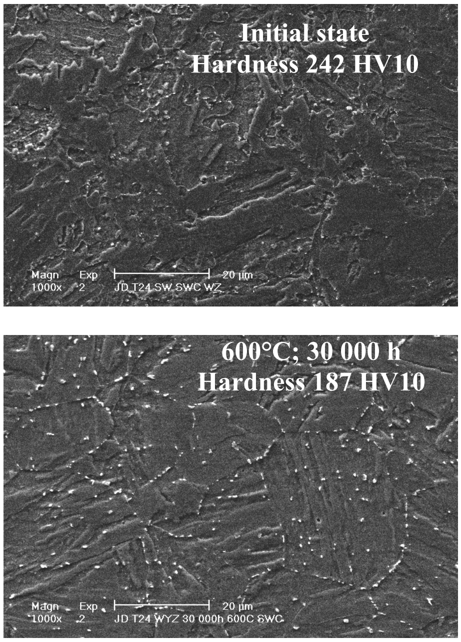


Fig. 15. Structure of heat-affected zone of homogeneous circumferential welded joint made of 7CrMoVTiB10-10 steel after long-term annealing at elevated temperature, observed under scanning electron microscope (mag. 1000x): a) in initial state, b) at 600°C after 30,000 hours

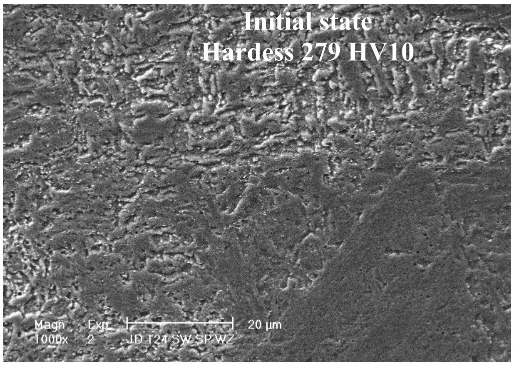
4.3. Effect of long-term annealing on fractography of fractured impact test samples of 7CrMoVTiB10-10 steel and welded joint

The fractographic examinations of impact test samples fractured with an impact hammer were carried out under scanning electron microscope. The observations were made on fractures obtained on parent material and in weld metal at room temperature.

Fractures obtained for tested 7CrMoVTiB10-10 steel in initial state are ductile in nature (Fig. 17a). Long-term annealing at 600°C for even up to 30,000 hours revealed mixed fractures with a predominance of ductile fracture over the brittle areas, whereas after annealing at 550°C for 30,000 hours brittle fractures with visible cleavage planes, but also with the share of rather numerous ductile areas, were observed (Fig. 17b).

Fractures of impact test samples fractured in the weld metal of homogeneous circumferential welded joint at room temperature are characterised by mixed fracture with a predominance of the brittle one, whereas fractures obtained in weld after 10,000 hours, regardless of test temperature - 550 and 600°C, are also mixed in nature, however with a predominance of ductile areas over the brittle ones (Fig. 18a). Similar nature is observed in fracture obtained after annealing at 600°C for 30,000 hours, whereas after annealing at 550°C for 30,000 hours mixed fracture with a distinct predominance of the brittle one was revealed (Fig. 18b).

a)



b)

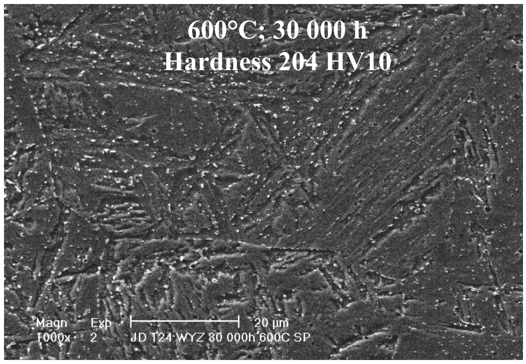
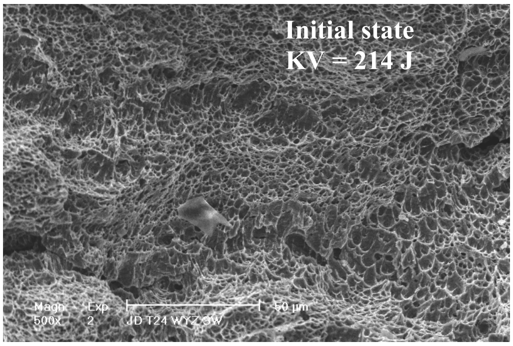


Fig. 16. Structure of weld metal of homogeneous circumferential welded joint made of 7CrMoVTiB10-10 steel after long-term annealing at elevated temperature, observed under scanning electron microscope (mag. 1000x): a) in initial state, b) at 600°C after 30,000 hours

a)



b)

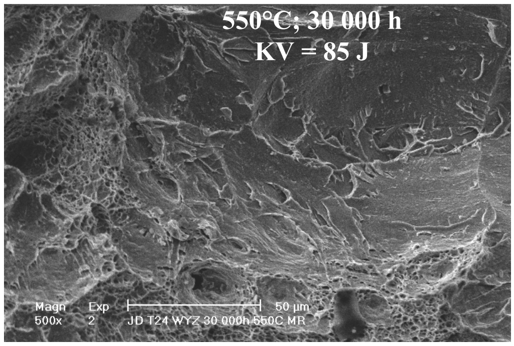
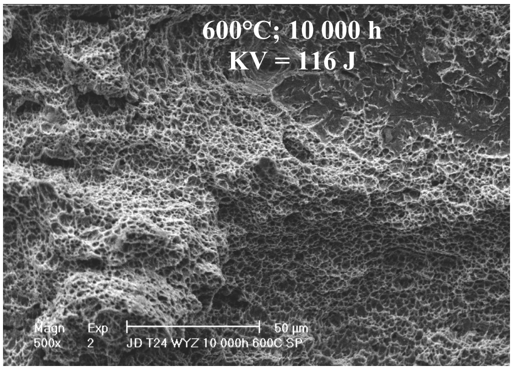


Fig. 17. Fractography of impact test samples of 7CrMoVTiB10-10 steel after long-term annealing at elevated temperature, observed under scanning electron microscope (mag. 500x): a) in initial state, b) at 550°C after 30,000 hours

a)



b)

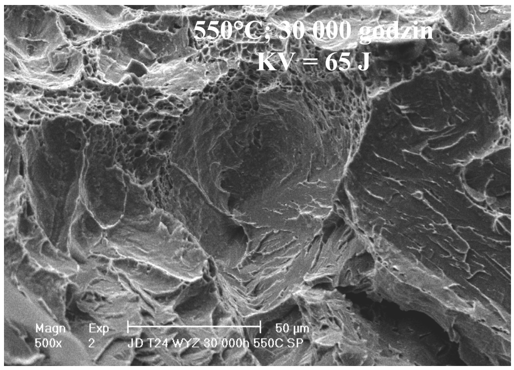


Fig. 18. Fractography of impact test samples of the weld of homogeneous circumferential welded joint made of 7CrMoVTiB10-10 steel after long-term annealing at elevated temperature, observed under scanning electron microscope (mag. 500x): a) at 600°C after 10,000 hours, b) at 550°C after 30,000 hours

5. Conclusions

The examinations of low-alloy bainitic steel 7CrMoVTiB10-10 (P24) allow finding out that:

1. After long-term annealing at 550 and 600°C for up to 10,000 hours, no significant changes in the image of microstructure as well as no significant changes in mechanical and plastic properties and hardness were observed.
2. In the microstructure of tested steel after long-term annealing at 550°C for up to 30,000 hours, only insignificant decay of the bainite areas and occurrence of carbide precipitations inside grains and at grain boundaries of primary austenite were observed.

3. In the microstructure image of tested steel after annealing at 600°C for up to 30,000 hours, a partial decay of the bainite areas with carbide precipitations inside grains and at grain boundaries of primary austenite, which form chains in places, was observed.
4. In spite of changes in the microstructure, the mechanical properties of 7CrMoVTiB10-10 steel are maintained at sufficiently high level after long-term annealing for up to 30,000 hours, whatever the test temperature was. They meet the expectations and requirements for steel products made of this steel in as-delivered state.
5. Changes in microstructure of the material of homogeneous welded joint made of 7CrMoVTiB10-10 steel caused the reduction in mechanical properties after annealing at 550 and 600°C for 30,000 hours, at the same time resulting in increase in their plastic properties (Elongation, KV) in some cases. These changes also caused the reduction in hardness after long-term annealing.

References

[1] F. Masuyama, Steam plant material developments in Japan, Proceedings of the 6th International Conference on Materials for Advanced Power Engineering, Liege, 1998, 1087.

[2] F. Deshayes, W. Bendick, K. Haarmann, J.C Vaillant, New 2-3%Cr Steel Grades for waterwall panels and superheaters raport COST 501, Liege, 1998.

[3] A. Hernas, T. Wala, Selection of materials for superheaters with improved performance parameters, Materials and technologies for construction of supercritical boilers and waste incinerators, House of the Polish Association of Metallurgical Engineers and Technicians (SITPH), Katowice, 2009, 154-171 (in Polish).

[4] J. Dobrzański, A. Zieliński, A. Hernas, Structure and properties of new creep-resisting ferritic-matrix steels, Materials and technologies used for construction of supercritical boilers and waste incinerators, House of the Polish Association of Metallurgical Engineers and Technicians (SITPH), Katowice, 2009, 47-101 (in Polish).

[5] J. Dobrzański, A. Zieliński, M. Sroka, Structure, properties and method of the state evaluation of low-alloyed steel T23 (HCM2S) worked in creep conditions, Proceedings of the 11th International Scientific Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science, Gliwice-Zakopane, 2005.

[6] J. Dobrzański, A. Zieliński, J. Pasternak, A. Hernas, Experience in the use of new steels for manufacturing of components of boilers for supercritical parameters, Periodical “Prace IMZ” 62/1 (2009) 51-60 (in Polish).

[7] H. Heuser, Filler metals for welding of T/P23 and T/P24, The Scientific and Technical Conference, Rudy Raciborskie, 2009 (in Polish).

[8] J. Dobrzański, S. Fudali, J. Pasternak, W. Zabłocki, Experience in possibility of using T/P24 and VM12 steels under domestic conditions, Proceedings of the Scientific and Technical Conference, Rudy Raciborskie, 2007 (in Polish).

[9] J. Dobrzański, J. Pasternak, Possibilities of using new low-alloy bainitic steels for membrane walls of boilers with supercritical parameters under large domestic manufacturer conditions, Periodical “Prace IMiUE” 23 (2009) 127-152 (in Polish).

[10] H. Paszkowska, A. Zieliński, Assessment of usability of low-alloy steel 7CrMoVTiB10-10 (P24) after service in boilers with supercritical working parameters, Proceedings of the Works of the 38th School of Materials Science, SIM’2010, Krynica, 2009, 429-433 (in Polish).

[11] J. Dobrzański, J. Pasternak, Mechanical properties and structure of low-alloy steels 7CrWVNb9-6 and 7CrMoVTiB10-10 for components of evaporator collectors of boilers with supercritical working parameters, Proceedings of the 2nd Welding Conference "Powerwelding-2011", Kroczyce-Ostaniec, 2011 (in Polish).

[12] J. Dobrzański, A. Zieliński, S. Fudali, Effect of the initial state structure and conditions of welding 7CrMoVTiB10-10 steel on quality of welded joints of gas-tight water walls in boilers with supercritical working parameters, Proceedings of the Welding Conference "Powerwelding-2010", Ustroń, 2011 (in Polish).

[13] J. Dobrzański, K. Radwański, Effect of the initial state structure of 7CrMoVTiB10-10 (T24) steel on quality of welded joints of evaporator tight walls in boilers with supercritical working parameters, Power Industry, Thematic Worksheet 21 (2010) 40-44 (in Polish).

[14] J. Dobrzański, J. Pasternak, Properties and application of welded joints in heat resisting bainitic and martensitic steels, Proceedings of the 25th International Conference “Welding 2008”, Subotica, Serbia, 2008, 137.

[15] J. Dobrzański, J. Pasternak, Properties selection and evaluation of welded joints made of new generation creep-resisting steel - a decisive factor accounting for reliability and safety of the power equipment, Welding in the World 52 (2008) 429-436.

[16] J. Dobrzański, J. Pasternak, Properties evaluation and applications of base materials and welded joints made from new generation bainitic creep-resisting steels, Proceedings of the 41st Kraftwerkstechnisches Colloquium 2009, Sichere und nachhaltige Energieversorgung, Betrieb und Instandhaltung, Dresden, 2009, poster P22.

[17] J. Dobrzański, J. Pasternak, Reliability and safety of the power equipment in respect of properties evaluation of welded joints made from new generation creep-resisting steels, ASME, Pressure Vessels and Piping Division 6/B (2010) 1717-1730.

[18] J. Dobrzański, J. Pasternak, A. Zieliński, Evaluation of base material and welded joints designated for membrane wall components made from low-alloy steels in large boilermaker conditions, Proceedings of the 9th Liege Conference on Materials for Advanced Power Engineering, Liege, 2010, 390-399.

[19] J. Dobrzański, Structure and properties of new bainitic and martensitic steels, Legal and technical conditions for construction and modernisation of power boilers, ordered research paper, Materials of the Office of Technical Inspection Seminar, “Akademia UDT” Publishing House, Gliwice, 2010 (in Polish).