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Mechanical properties of Cr-Mo and Cr-Mo-V low-alloy steel welded joints after long-term service under creep conditions

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ABSTRACT

Purpose: The purpose of this paper was to evaluate mechanical properties of 13CrMo4-5 and 14MoV6-3 steel homogeneous circumferential welded joints after long-term service under creep conditions much beyond the design work time of 100,000 hours and their suitability for further service.

Design/methodology/approach: Mechanical properties of individual elements of welded joints in non-destructive tests were determined. In particular, the brittle fracture appearance transition temperature as well as strength and plastic properties at room and elevated temperature were determined.

Findings: The influence of long-term service on strength and plastic properties and on impact strength of tested material of 13CrMo4-5 and 14MoV6-3 steel homogeneous circumferential welded joints after long-term service under creep conditions beyond the design work time was determined.

Research limitations/implications: The evaluation of suitability of the applied test methods in extension of service period for materials of welded joints of elements working under creep conditions after having exceeded the design work time was made.

Practical implications: The obtained test results are used in creation of materials characteristics to allow predicting the life time of tested steels and their welded joints and are used for condition assessment and prediction about further operation of welded joints of elements in the pressure part of power equipment working under creep conditions.

Originality/value: The applied methodology and developed materials characteristics are used for condition assessment and prediction about further safe operation of welded joints of elements in the pressure part of power equipment working under creep conditions.

Keywords: Welded joint mechanical properties; Homogeneous circumferential welded joint; Cr-Mo steel; Cr-Mo-V steel

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MATERIALS

1. Introduction

At present, a definite majority of power units in Poland has reached or significantly exceeded the assumed design life time of 100,000 or 200,000 hours. Therefore, the electric energy manufacturers direct their main efforts at maintaining the existing power units available with simultaneous provision of their safe operation. The inspections of and repairs to power installations under operation whose design work time was most often significantly exceeded along with simultaneous reliable rational diagnostics seems to be the proper way for accomplishment of these aims. However, in order to maintain the current level of electric energy and heat production in Poland, the periodic inspections and repairs are not sufficient. The modernisation of the operated units is required too. This modernisation must include not only repairs, but also the replacement of some of the elements. These operations always require first of all the condition assessment of materials and elements under operation and forecasting about further safe service at working parameters.

The subject of this paper is the evaluation of mechanical properties of circumferential welded joints of critical elements of low-alloy steel boilers after long-term service under creep conditions beyond the design work time of 100,000 and 200,000 hours and their suitability for further service. Research methods and procedures will be proposed to determine the characteristics of mechanical properties of materials.

2. Material for investigations

The material for investigations was 13CrMo4-5 and 14MoV6-3 low-alloy steel homogeneous circumferential welded joints of elements of the pressure part of boiler after long-term service under creep conditions for a time that has significantly exceeded the assumed one. The tests were carried out on the following test pieces:

- 14MoV63 (13HMF) steel primary steam pipeline after 200,000 h service (Fig. 1);
- 13CrMo4-5 (15HM) steel II° secondary steam superheater header after 140,000 h service (Fig. 2).

Chemical composition of steels tested with regard to the requirements of standard is presented in Table 1.

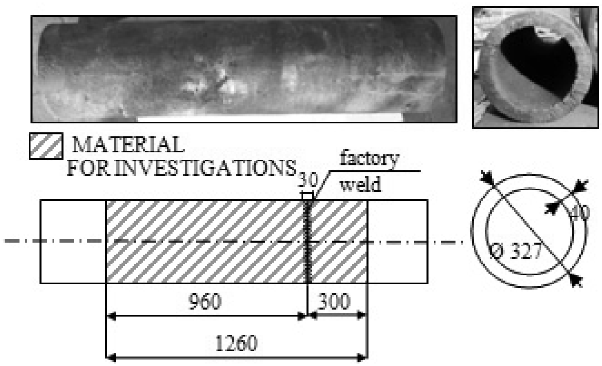


Fig. 1. Material for investigations in the form of 14MoV63 steel homogeneous circumferential welded joint of primary steam pipeline elbow shell after 200,000h service

The results of check analysis of chemical composition of tested steels revealed that the materials of the examined test piece of 14MoV6-3 steel primary steam pipeline elbow and section of 13CrMo4-5 steel II° secondary steam superheater inlet header met the requirements of standard with regard to chemical composition of tested steels.

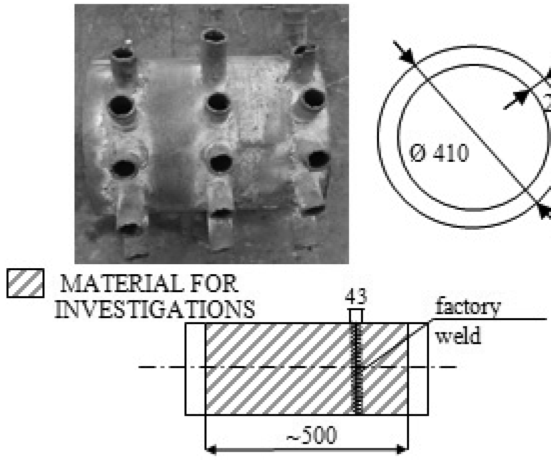


Fig. 2. Material for investigations in the form of 13CrMo4-5 steel homogeneous circumferential welded joint of II° secondary steam superheater inlet header shell after 140,000 h service

Table 1a.
Check analysis of chemical composition of the material of examined test piece of 14MoV6-3 steel primary steam pipeline after 200,000 h service under creep conditions

	Content of elements [%]						
	C	Si	Mn	Cr	Mo	Ni	V
PN-75/H-84024	0.10-0.18	0.15-0.35	0.40-0.70	0.30--0.60	0.50-0.65	≤0.30	0.22-0.35
Check analysis	0.12	0.25	0.51	0.35	0.52	0.051	0.23

Table 1b.
Check analysis of chemical composition of the material of examined test piece of 13CrMo4-5 steel II° secondary steam superheater inlet header after 140,000 h service under creep conditions

	Content of elements [%]					
	C	Si	Mn	Cr	Mo	Ni
PN-75/H-84024	0.11-0.18	0.15-0.35	0.40-0.70	0.7-1.0	0.40-0.55	≤0.35
Check analysis	0.15	0.23	0.58	0.89	0.43	0.096

3. Range of investigations

As a part of the tests, the mechanical properties of the material of welded joints were determined. The results of the following tests were used for assessment of material condition and required functional properties of welded joints:

- strength and plastic properties at room and elevated temperature,
- influence of temperature on mechanical properties of welded joints;
- impact strength of individual elements of the joints with determination of nil ductility transition temperature.

The obtained test results are the verification of proposed method for assessment and prediction about the time of further safe service of Cr-Mo and Cr-Mo-V steel homogeneous circumferential welded joints. Their positive results allow the adopted procedures to be used in materials diagnostics performed as a part of direct orders from the industry.

4. Test results

4.1. Mechanical testing

For the examined circumferential welded joints:

- from 13CrMo4-5 steel after 140,000 h service under creep conditions;
- from 14MoV6-3 steel after 200,000 h service under creep conditions, of elements in the pressure part of boiler the evaluation of strength properties at room and elevated temperature and impact strength was made.

The investigations of strength properties of the materials of elements of joints in the examined test piece of inlet header and primary steam pipeline after long-term service working under creep conditions were carried out in the tensile test at room temperature to determine the tensile strength (R_m), yield point (R_e), elongation (A_5) and reduction of area (Z) and at elevated temperature T_b = 200, 300, 400, 450, 500°C to determine the tensile strength (R_m^t), yield point (R_e^t), elongation (A_5^t) and reduction of area (Z^t). The sampling method, designation and areas where examinations of strength properties were made are shown in Fig. 3.

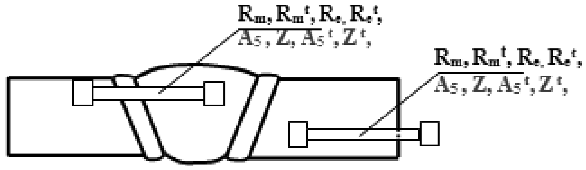


Fig. 3. Sampling method, designation and areas where examinations of strength and plastic properties of the material of 14MoV6-3 steel primary steam pipeline after 200,000h service and the material of 13CrMo4-5 steel inlet header after 140,000h service were made

The results of mechanical testing for parent material of the examined test piece of inlet header and primary steam pipeline at room temperature, in particular: tensile strength R_m, yield point R_e and elongation A_5, are presented in columns 4-6 of Table 2, while the results for yield point R_e^t at temperature similar to the service temperature of 500°C - in column 7 of the above-mentioned table.

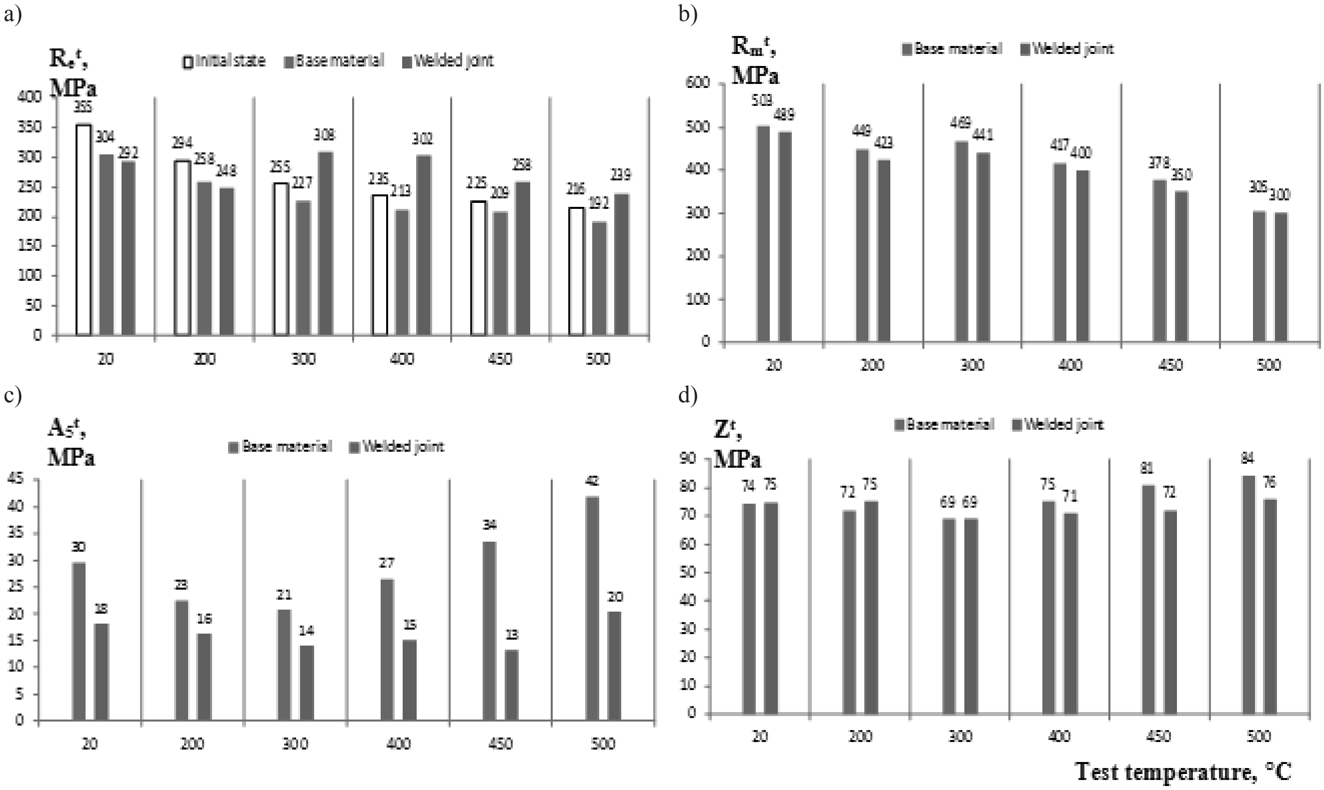


Fig. 4. Comparison of the results of tests of the following parameters at room and elevated temperature for material in initial state and material of shell and circumferential welded joint of test piece of the 14MoV6-3 steel primary steam pipeline after 200,000 h service under creep conditions: a) yield point R_e, R_e^t,b) tensile strength R_m, R_m^t, c) elongation A_5^t, d) reduction of area Z^t

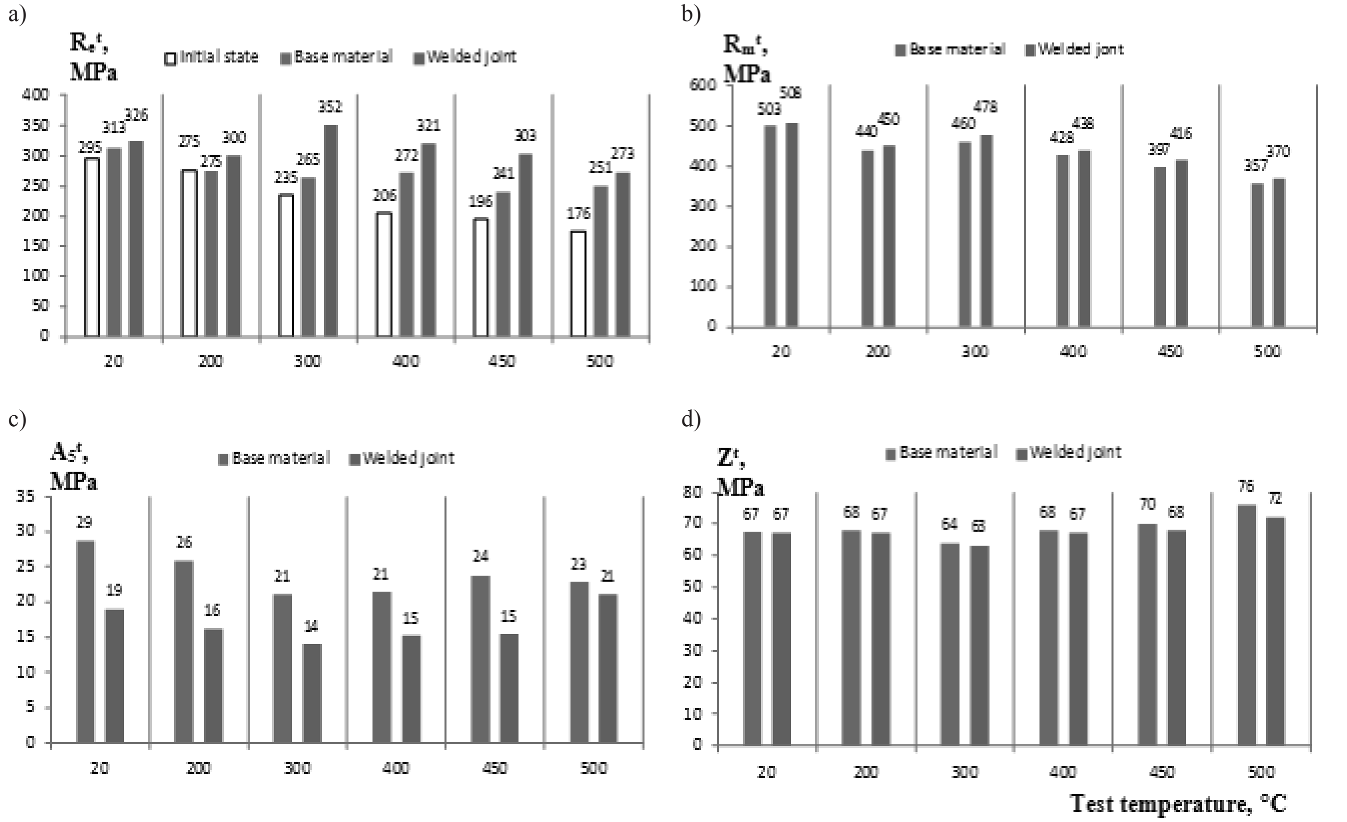


Fig. 5. Comparison of the results of tests of the following parameters at room and elevated temperature for material in initial state and material of shell and circumferential welded joint of test piece of the 13CrMo4-5 steel II° secondary steam superheater inlet header after 140,000 h service under creep conditions: a) yield point R_e^t, b) tensile strength R_m, c) elongation A_5^t, d) reduction of area Z^t

The results of the above-mentioned tests are also summarised in graphic form and compared to the obtained results depending on test temperature for parent material and welded joint of the examined test piece of inlet header (Fig. 4) and primary steam pipeline (Fig. 5).

The results of strength tests allow to find out whether the examined materials meet the requirements of strength indicators provided in respective standards for metallurgical products from the examined steel grade or not.

The examined test piece of the primary steam pipeline:

- for parent material and welded joint meets the requirements of tensile strength at room temperature R_m for 14MoV6-3 steel after normalising and tempering according to PN-74/H-74252;
- for parent material and welded joint does not meet the requirement of min. yield point at room temperature Re min for 14MoV6-3 steel after normalising and tempering according to PN-74/H-74252;
- for parent material meets the requirement of min. elongation A5 at room temperature for 14MoV6-3 steel in initial state after normalising and tempering according to PN-74/H-74252, while for welded joint in this steel does not meet the requirement;
- for welded joint meets the requirement of min. yield point R_e^t for 14MoV6-3 steel after normalising and tempering at 300, 400, 450, 500°C according to PN-74/H-74252, while for material at 300, 400, 450, 500°C does not meet the requirement. At 200°C, this requirement is met for neither parent material nor welded joint.

The examined test piece of the II° secondary steam superheater header:

- for parent material and welded joint meets the requirements of tensile strength at room temperature Rm for 13CrMo4-5 steel after normalising and tempering according to PN-74/H-74252;
- for parent material and welded joint does not meet the requirement of min. yield point at room temperature Re min for 13CrMo4-5 steel after normalising and tempering according to PN-74/H-74252;
- for parent material meets the requirement of min. elongation A5 at room temperature for 13CrMo4-5 steel in initial state after normalising and tempering according to PN-74/H-74252, while for welded joint in this steel does not meet the requirement;
- for parent material and welded joint meets the requirement of min. yield point Ret for 13CrMo4-5 steel after normalising and tempering at 200, 300, 400, 450, 500°C according to PN-74/H-74252.

Table 2.
Results of mechanical testing of examined test pieces: material of primary steam pipeline shell after 200,000 h service under creep conditions and material of II° secondary steam superheater inlet header shell after 140,000 h service under creep conditions

Name of element	Steel grade Dimensions, mm	Test piece designation	Mechanical properties			
			R_m	R_e	A_5	$R_{p0.2}^{500}$
			MPa	MPa	%	MPa
1	2	3	4	5	6	7
Material of primary steam pipeline elbow shell	14MoV6-3 (13HMF)[1)] ϕ 327x40	marked MR1	503	304	30.0	192[1.)]
REQUIREMENTS FOR MATERIAL IN INITIAL STATE ACC. TO BN-74/H-0648-67			490-690	min. 365	min. 18	min. 216
Material of 13CrMo4-5 steel II° secondary steam superheater inlet header shell	13CrMo4-5 (15HM)[1)] ϕ 410x20	marked MR2	503	313	29.0	251[1.)]
REQUIREMENTS FOR MATERIAL IN INITIAL STATE ACC. TO PN-74/H-74252			440-570	min. 295	min. 22	min. 176

[1)] markings according to standards applicable in initial state

4.2. Impact tests

The impact tests were carried out on longitudinal samples with V-notch cut in perpendicularly to the shell surface of the examined primary steam pipeline and II° secondary steam superheater inlet header after long-term service under creep conditions. The designations and areas where impact tests for the examined welded joints were carried out are shown in Fig. 6.

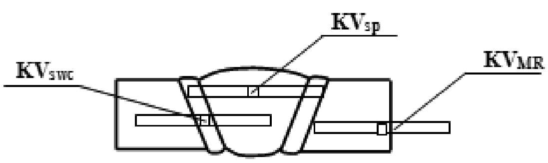
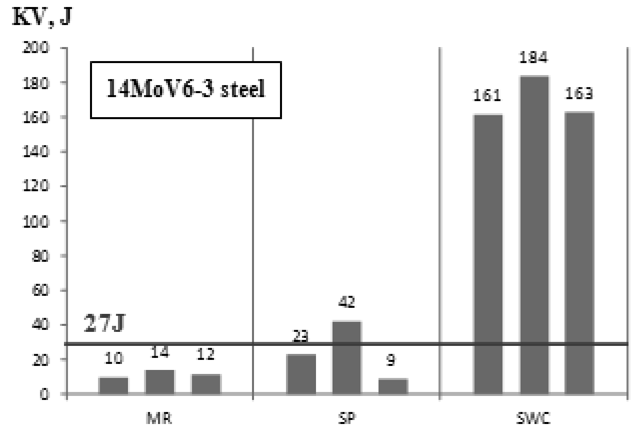


Fig. 6. Designation and areas where impact tests for material of 14MoV6-3 steel primary steam pipeline after 200,000 h service and material of 13CrMo4-5 steel inlet header after 140,000 h service were carried out

The obtained test results for the material of 14MoV6-3 steel primary steam pipeline shell at room temperature were compared to those obtained at the same temperature for the homogeneous circumferential welded joint elements, in particular impact energy measured in heat-affected zone and weld, which is shown in Fig. 7a. Similarly, the comparison of the results of impact tests at room temperature was made for materials of 13CrMo4-5 steel homogeneous circumferential welded joint elements of the II° secondary steam superheater inlet header shell, which is shown in Fig. 7b. The obtained test results for the parent material and the material of weld and heat-affected zone of the primary steam pipeline and II° steam superheater inlet header do not meet the requirements for material in initial state as well as the adopted required minimum limit value of 27 J.

In addition, the impact tests depending on test temperature were carried out for materials of welded joint elements (parent material, heat-affected zone material and weld material) of the 14MoV6-3 steel primary steam pipeline (Fig. 8) and the 13CrMo4-5 steel II° steam superheater inlet header (Fig. 9) to determine the brittle fracture appearance transition temperature.

a)



b)

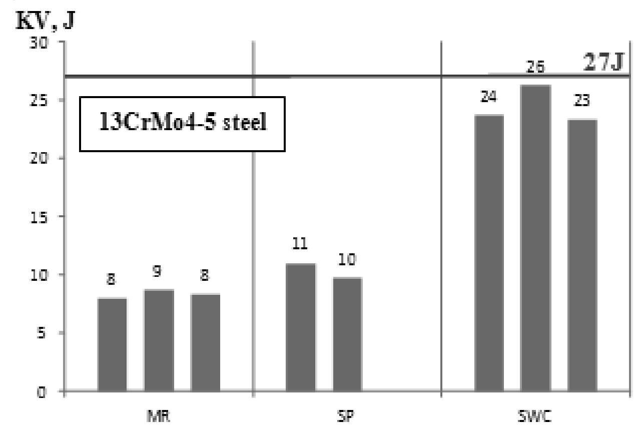
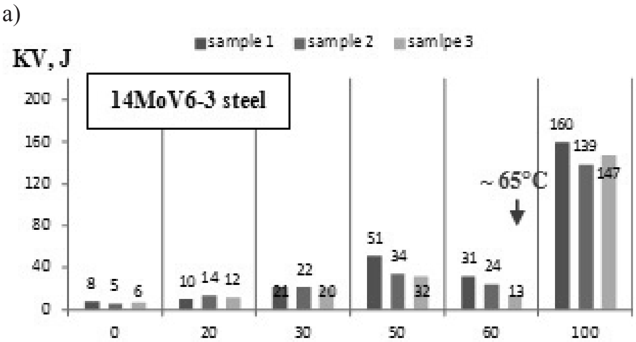


Fig. 7. Comparison of impact test results at room temperature for materials of homogeneous circumferential welded joint elements - parent material (MR), heat-affected zone material (SWC), weld material (SP) for: a) primary steam pipeline after 200.000 h service under creep conditions; b) II° secondary steam superheater inlet header after 140,000 h service under creep conditions

As compared to the as-received state, the brittle fracture appearance transition temperature for materials of tested elements is shifted towards its higher values. Only in few cases the material after long-term service under creep conditions is characterised by impact strength level with values higher than the minimum value required for material in as-received metallurgical state. Based on long-standing experience, it has been found out that the value of impact strength does not depend exclusively on development of precipitation processes due to creeping, but also on development of internal damages and structural discontinuities occurred during service. Thus, it can be found out that the method for impact testing on material after service under creep conditions is not directly suitable for evaluation of residual life and determination of exhaustion extent. However, it is suitable for evaluation of material's ability to transfer loads related to performed pressure tests as well as shutdowns and start-ups of the installation during its further service.

The comparison of the results of averaged impact strength measured on V-notch samples depending on test temperature for the parent material and weld is presented for the primary steam pipeline in Fig. 10 and for the secondary steam inlet header in Fig. 11, respectively.

a)



b)

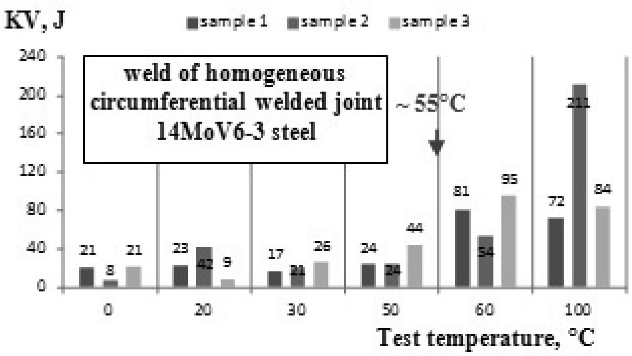
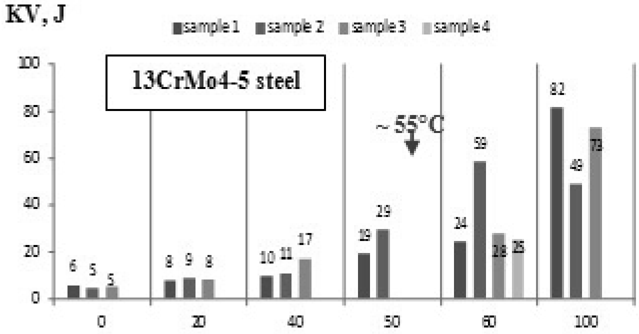


Fig. 8. Test results of impact energy measured on V-notch samples depending on test temperature between 0 and 100°C for test piece of the primary steam pipeline after 200,000 h service under creep conditions: a) parent material, b) weld

At the same time, the brittle fracture appearance transition temperature level has been determined (Figs. 10, 11, Table 3), which is approx. +65°C for the primary steam pipeline and approx. +55ºC for the weld material of homogeneous circumferential welded joint. The brittle fracture appearance transition temperature for the material of the secondary steam inlet header is approx. +55°C and for the weld of homogeneous circumferential welded joint - approx. +90°C.

a)



b)

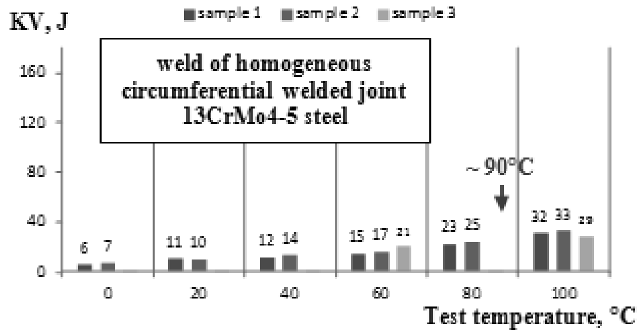


Fig. 9. Test results of impact energy measured on V-notch samples depending on test temperature between 0 and 100°C for test piece of the II° secondary steam superheater inlet header after 140,000 h service under creep conditions: a) parent material, b) weld

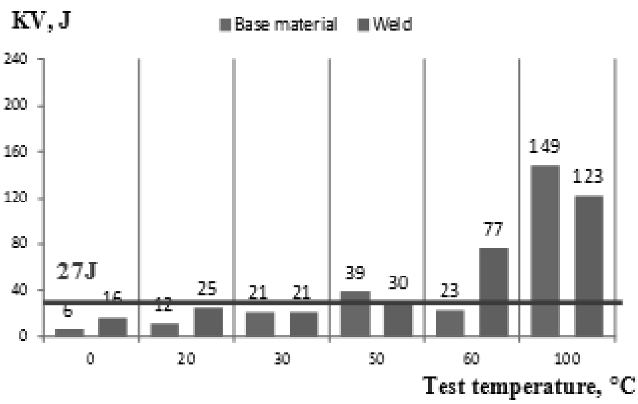


Fig. 10. Comparison of test results of impact energy measured on V-notch samples depending on test temperature between 0 and 100°C for the parent material and weld of test piece of the 14MoV6-3 steel primary steam pipeline after 200,000 h service under creep conditions

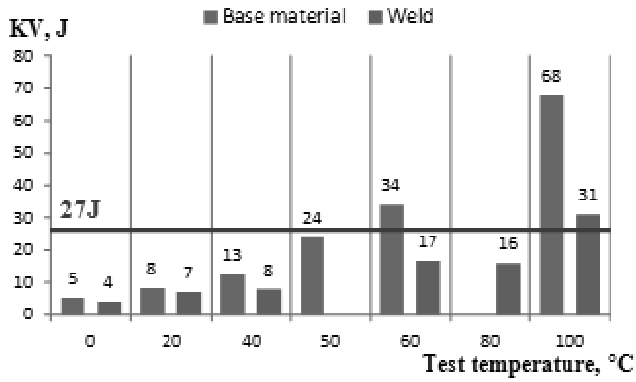


Fig. 11. Comparison of test results of impact energy measured on V-notch samples depending on test temperature between 0 and 100°C for the parent material and weld of test piece of the 13CrMo4-5 steel II° secondary steam superheater inlet header after 140,000 h service under creep conditions

The occurrence of welded joint whose materials of elements have such low impact energy values in industrial practice requires particular caution to be exercised with regard to the method for conducting water pressure tests and close compliance with applicable procedures for starting up and shutting down the boiler.

Table 3.
Comparison of impact test results for the examined elements of welded joints of 14MoV6-3 steel primary steam pipeline after 200,000 h service and the material of 13CrMo4-5 steel inlet header after 140,000 h service

Type of element	Steel grade	Service time, h	Testing area	KV 20°C, J	$FATT_{50}$
Primary steam pipeline	14MoV6-3 (13HMF)	>200 000	MR	12	~65
			SWC	169	not performed
			SP	24	~55
II° steam superheater outlet header	13CrMo4-5 (15HM)	140 000	MR	8	~55
			SWC	24	not performed
			SP	10	~90

5. Conclusions

The investigations of mechanical properties of the 13CrMo4-5 and 14MoV6-3 steel circumferential welded joint after long-term service under creep conditions allow to find out that:

1. The examined test pieces of the II° secondary steam superheater inlet header and primary steam pipeline after long-term service meet the requirements for tensile strength at room temperature.
2. The examined test piece of the II° secondary steam superheater inlet header after long-term service meets the requirements for yield point at room temperature according to the requirements provided in relevant standards for metallurgical products, whereas the examined section of the primary steam pipeline after long-term service does not meet the requirements for yield point at room temperature according to the requirements provided in relevant standards for metallurgical products from the examined steel grade.
3. With regard to yield point R_e^t at elevated temperature, similar to service temperature, the material of test piece of the 13CrMo4-5 steel II° secondary steam superheater inlet header meets the requirements provided in relevant standards for metallurgical products, whereas the material of test piece of the 14MoV6-3 steel primary steam pipeline II does not meet this requirement. However, it does not show the loss of suitability of such a material for further service.
4. As a result of long-term service, the shift of brittle fracture appearance transition temperature towards higher values - positive temperatures, was observed in materials of test pieces of the II° secondary steam superheater inlet header and primary steam pipeline. This temperature for the material of examined primary steam pipeline is approx. +65°C, while for the weld material of circumferential welded joint is only approx. +55°C. The brittle fracture appearance transition temperature for the material of the secondary steam inlet header is approx. +55°C and for the weld of circumferential welded joint - approx. +90°C.
5. The knowledge of basic mechanical properties of parent material and welded joints at room and elevated temperature, after long-term service higher than the design work time, allows the evaluation of ability to transfer loads required in conducted water pressure tests, selection of proper parameters for these tests and possible verification of the way of starting up and shutting down the boiler.
6. The evaluation of the ability to transfer running loads by the examined materials after service for temperature and stress parameters lower than and/or equal to the working ones is made based on the determined residual life and disposable residual life and the microstructural investigations aimed at evaluation of its condition, class and estimation of the exhaustion extent. Such investigations are conducted for the examined welded joints.

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