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PROPERTIES OF THE SECONDARY STEAM PIPELINES WITH WELDED JOINTS OPERATING UNDER CREEP CONDITIONS IN THE ASSESSMENT OF SUITABILITY FOR LONG-TERM SERVICE

The research aimed to assess the condition of the main steam pipelines and peripheral welded joints after long-term exploitation under creep conditions that operated for a time significantly exceeding the design time. Secondary steam pipeline elements made of 10CrMo9-10 steel operated for 240 000, 280 000, and 308 000 h were under investigation. The mechanical properties of the welded joint areas were determined in destructive tests. In particular, the brittle transition temperature and mechanical and plastic properties at room and elevated temperatures were determined. The effect of long-term operation on the tested pipelines' strength, plastic properties, and impact strength was also investigated. Based on the completed creep tests, the extrapolation method determined the residual life. The available residual life was estimated, which is the safe period of further operation for the operating parameters of stress σ_r and temperature T_r. The applied methodology and the adopted procedure will be used to assess the condition and further operation time prediction of welded joints of power equipment pressure parts operating under creep conditions.

Keywords: Welded joint; creep condition; long-term service; degradation; creep test

1. Introduction

The operating time of most power units significantly exceeded the design time, often more than twice. Therefore, electricity producers focus their primary efforts on maintaining the availability of existing power plants while ensuring their safe service. Modernizing the exploited units aims to improve their efficiency and effectiveness, considering the growing requirements for environmental protection and extending the safe operation time well beyond the design time [1-4,7].

This modernization must include repairs and replacement of some components. These procedures always require, first of all, an assessment of the materials and components' condition and a forecast of further safe operation for the working parameters of long-term service [1,4].

The following study assesses the condition of steam pipelines made of 10CrMo9-10 steel after long-term service under creep conditions exceeding the design service time of hours and their suitability for further operation. The steel is known for its high strength and resistance to corrosion and high temperatures, making it a popular choice in the energy industry, especially in the production of boilers and pipelines. Steel used for work at elevated temperatures not exceeding 580°C. Research methods and procedures will be proposed to determine the tested pipelines' properties and characteristics [6,9,10-14].

2. Material for research

The test material consisted of sections of the secondary steam pipeline made of 10CrMo9-10 (10H2M) steel after long-term operation under creep conditions for a time significantly exceeding the design time. The samples were taken from pipelines with the same operating parameters (temperature of exploitation 540°C, working pressure 3.31 MPa) but after different operating times: approximately 240 000 h, 280 000 h and 308 000 h under creep conditions.

The chemical composition of the tested materials after operation under creep conditions concerning the requirements of the subject standard is presented in TABLE 1.

The results of the control chemical composition analysis showed that the material of the secondary steam pipeline made of 10CrMo9-10 steel after 240 000, 280 000 and 308 000 h meets the standard requirements EN 10273.

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TABLE 1

Control analysis of the chemical composition of the tested material after long-term operation under creep conditions

Material type	Steel							
	C	Mn	Si	P	S	Cu	Cr	Mo
10CrMo9-10 after approx. 240 000 h	0.082	0.42	0.28	0.007	0.010	0.074	2.25	1.01
10CrMo9-10 after approx. 280 000 h	0,10	0,73	0,25	0,020	0,010	0,053	2,36	1,03
10CrMo9-10 after approx. 308 000 h	0,11	0,72	0,21	0,020	0,010	0,053	2,39	1,00
10CrMo9-10 EN 10273	**0.08 0.14**	**0.40 0.80**	**max. 0.50**	**max 0.020**	**max 0.010**	**max 0.30**	**2.00 2.50**	**0.90 1.10**

3. Scope of research

As part of the conducted tests, the properties of the material and the peripheral welded joint of the secondary steam pipeline after approximately 240 000, 280 000 and 308 000 h of operation were evaluated. The material condition assessment and the level of required performance properties included examining the following:

- mechanical and plastic properties at room and elevated temperatures (according to PN-75/H-84024),
- the temperature impact on the mechanical properties of welded joints and pipeline material (according to PN-75/H-84024),
- impact strength with determination of the brittle transition temperature (according PN-EN ISO148-1),
- residual creep strength in creep test (according PN-EN ISO204).

The obtained research results will verify the proposed method of assessing and predicting the time of further safe service of the pipeline material and welded joints made of 10CrMo9-10 steel. If the results are positive, the research method will be used in material diagnostics in the industry.

4. Test results

The mechanical properties of the material and welded joint of the secondary steam pipeline after long-term service under creep conditions were carried out at room temperature to determine the tensile strength (R_m), yield stress (R_e), elongation after fracture (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 (Z_t).

TABLE 2 presents the test results of selected mechanical properties for the initial material and the welded joint of the tested secondary steam pipelines at room temperature, in particular tensile strength, yield strength, elongation, and yield strength, respectively, at elevated temperatures close to the operating temperature of 500°C.

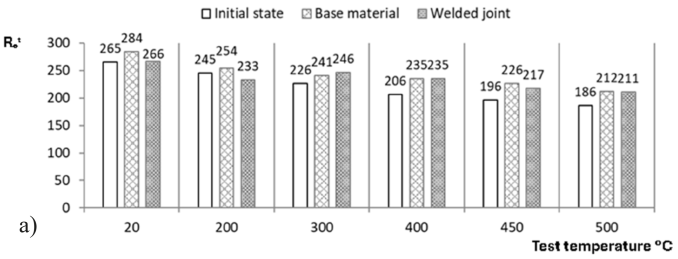
The test results were also presented graphically, and the obtained results were compared depending on the test temperature for the initial material and the welded joint of the tested secondary steam pipelines after approximately 240 000, 280 000, and 308 000 h of service under creep conditions (Figs. 1-3).

TABLE 2

Results of mechanical properties of base material and welded joints the secondary steam pipeline material after 240 000, 280 000 and 308 000 h of service under creep conditions

Element /Working time/ Pipeline designation	Steel grade dimensions [mm]	Tested sections designation	Mechanical properties			
			R_m	R_e	A_5	$R_{p0.2}^{500}$
			MPa	MPa	%	MPa
Material of secondary steam pipeline / 240 000 h	10CrMo9-10 Ø 508×16	Base material	474	284	33.0	212
Peripheral homogeneous joint 10CrMo9-10		Welded joint	473	266	21.0	211
Material of secondary steam pipeline / 280 000 h	10CrMo9-10 Ø 508×16	Base material	485	280	36.8	216
Peripheral homogeneous joint 10CrMo9-10		Welded joint	466	259[1)]	22.2	187
Material of secondary steam pipeline / 308 000 h	10CrMo9-10 Ø 508×16	Base material	492	297	31.6	236
Peripheral homogeneous joint 10CrMo9-10		Welded joint	489	288	27.8	233
REQUIREMENTS FOR 10CrMo9-10 STEEL IN THE INITIAL STATE ACCORDING TO PN-75/H-84024			**440÷590**	min 265	min 20	min 186

1) markings according to standards applicable in initial state



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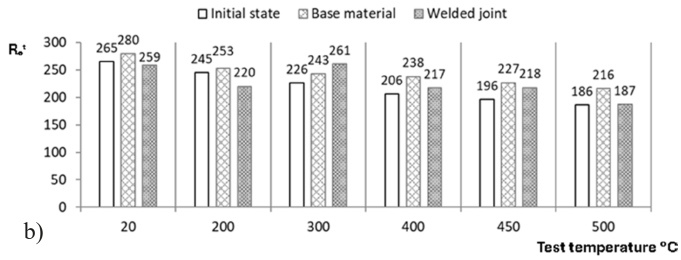

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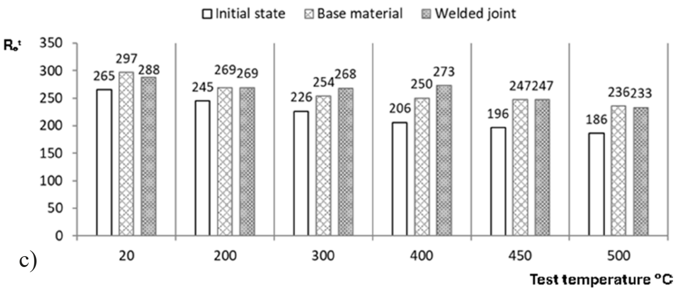
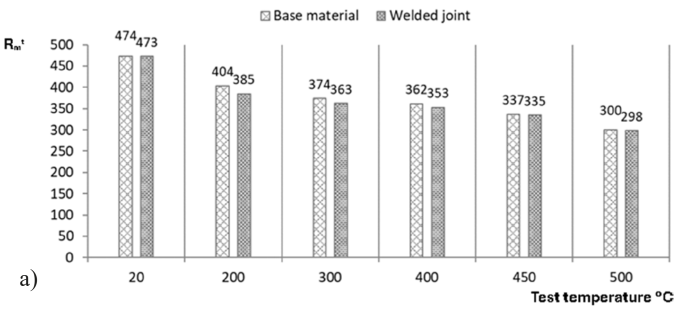


c)

Fig. 1. The yield strength result comparison at room and elevated temperature (R_e^t) of the material in the initial state, base material and the peripheral welded joint of the secondary steam pipeline section made of 10CrMo9-10 steel after approx.: a) 240 000 h, b) 280 000 h, c) 308 000 h operating under the creep conditions



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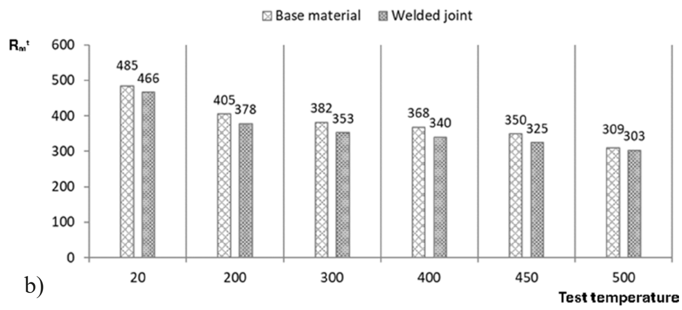

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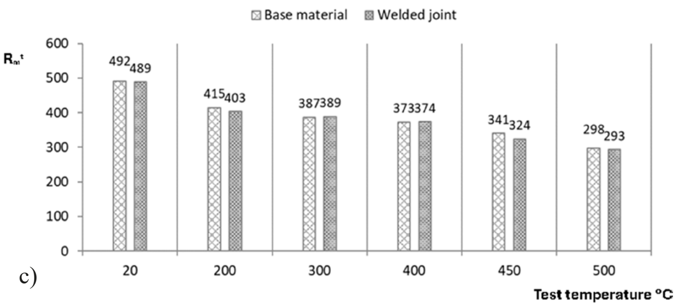

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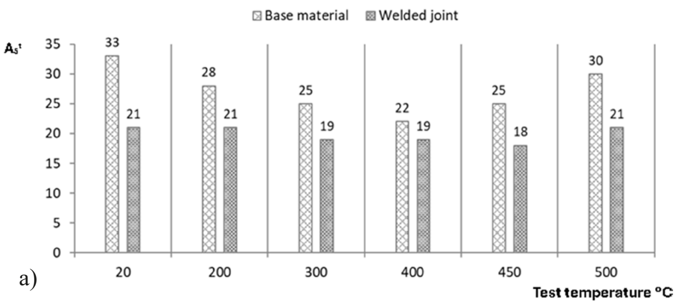
Fig. 2. The tensile strength result in comparison at room and elevated temperature (R_m^t) of the base material and the peripheral welded joint of the secondary steam pipeline section made of 10CrMo9-10 steel after approx.: a) 240 000 h, b) 280 000 h, c) 308 000 h operating under the creep conditions



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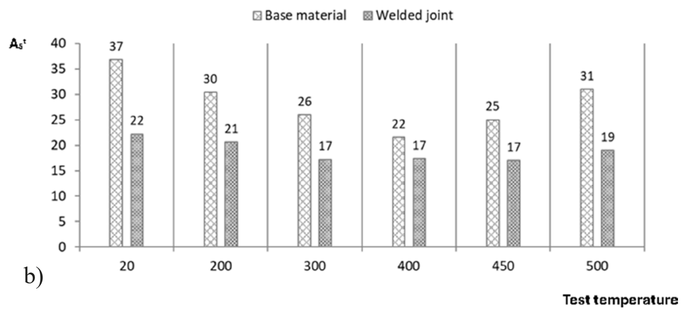

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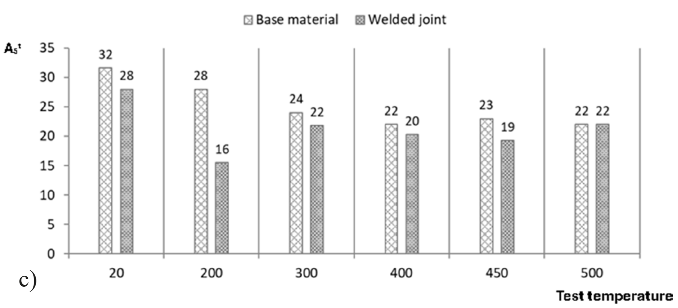

c)

Fig. 3. The elongation result in comparison at room and elevated temperature (A_5) of the base material and the peripheral welded joint of the secondary steam pipeline section made of 10CrMo9-10 steel after approx.: a) 240 000 h, b) 280 000 h, c) 308 000 h operating under the creep conditions

The strength test results allow us to determine whether the tested material meets the requirements of the above-mentioned strength indicators and the requirements of the subject standards for metallurgical products made of the tested steel grade.

Impact tests were carried out on longitudinal samples with a V-notch cut perpendicular to the casing surface of the tested secondary steam pipelines. Impact strength tests were performed depending on the test temperature for the secondary steam pipelines' base material and welded joint after 240 000, 280 000, and 308 000 h of service to determine the brittle transition temperature (Figs. 4-6).

In TABLE 3 the obtained impact test results for the base material and welded joint of secondary steam pipelines made of 10CrMo9-10 steel at room temperature and the level of the brittle transition temperature was compared.

Short creep tests were also performed on the tested materials and welded joints. The tests were carried out at a constant test stress level corresponding to the operating stress $\sigma_b = \sigma_r$ = const

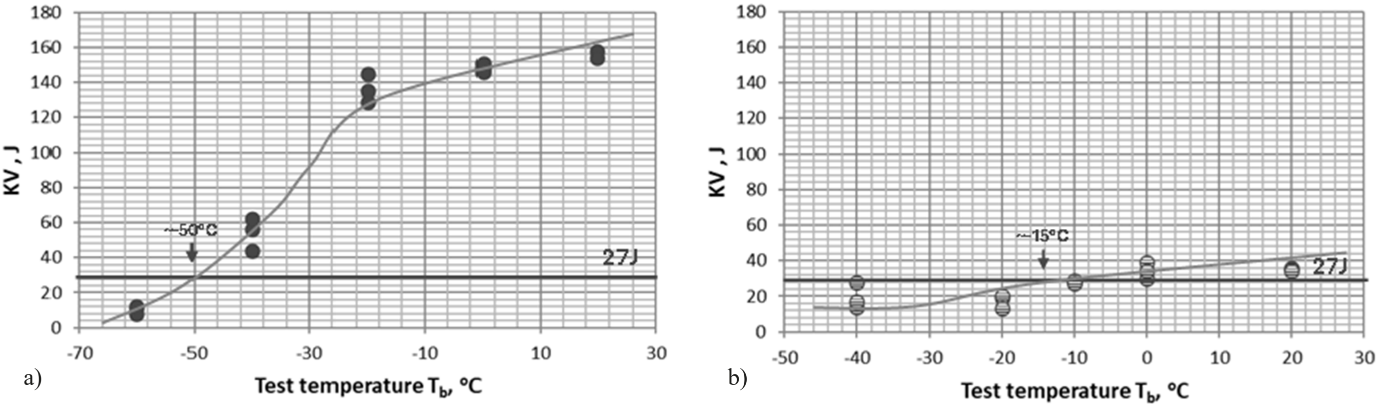

Fig. 4. The impact test results of the secondary steam pipeline sections after 240 000 h of operation under creep conditions: a) base material; b) welded joint

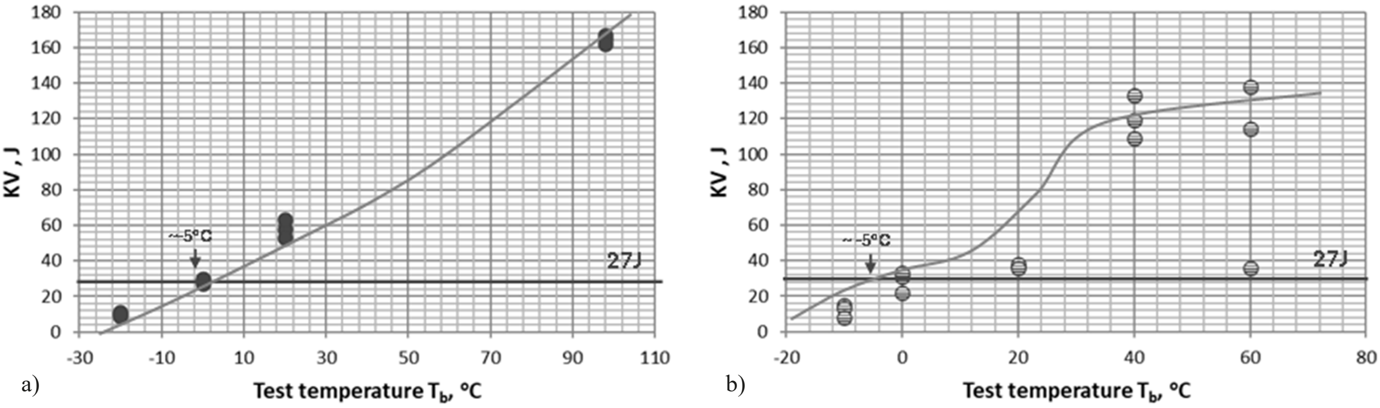

Fig. 5. The impact test results of the secondary steam pipeline sections after 280 000 h of operation under creep conditions: a) base material; b) welded joint

TABLE 3

The impact test results in a comparison of the tested welded joint elements after different service times operating under the creep conditions

Element	**Steel grade**	**Service time [h]**	**Tested sections designation**	**KV ~20°C [J]**	**FATT50 (Fracture Appearance Transition Temperature, 50% ductile fracture)**
secondary steam pipeline	10CrMo9-10	240 000	base material	167	~ –50
			heat affected zone	Not performed	Not performed
			welded joint	36	~ –15
		280 000	base material	58	ok. –5
			heat affected zone	150	ok. –-35
			welded joint	37	ok. –5
		308 000	base material	126	~ –25
			heat affected zone	Not performed	Not performed
			welded joint	Not performed	Not performed

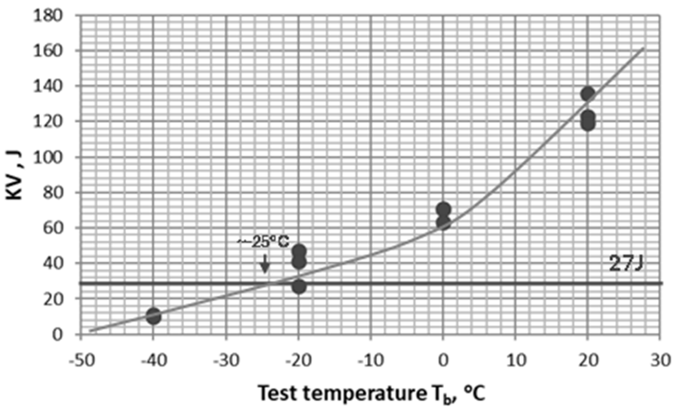

Fig. 6. The impact test results of the secondary steam pipeline base material after 308 000 h of operation under creep conditions

and at a continuous test temperature T_b for each test, but with different values from 620°C to 700°C in steps of 20°C.

The test results are presented as the relation $\log t_r = f(T_b)$ at σ_b = const., where t_r is the time to rupture in the creep test. They allow us to plot a straight line inclined to the time axis until the t_r is broken. The residual life is determined by extrapolating the obtained straight line towards a lower temperature corresponding to the operating temperature T_e.

The obtained results of the short creep tests of the material and the welded joint of the tested secondary steam pipeline made of 10CrMo9-10 steel after 240 000, 280 000, 308 000 h of operation under creep conditions conducted at a constant test stress level of σ_b = 55 MPa, corresponding to the assumed working σ_r for further operation, are presented in the form of the dependence $\log t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ in Figs. 7-9 and TABLE 4, respectively.

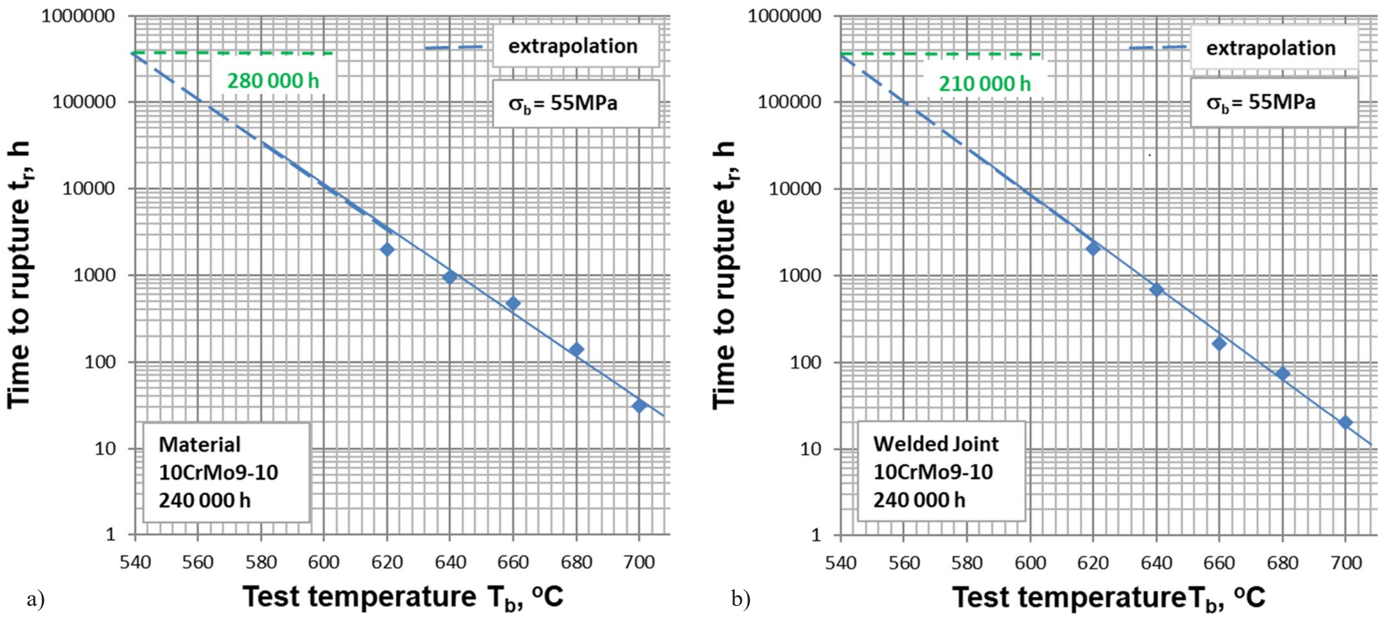

Fig. 7. Results of short creep tests of welded joint materials of the secondary steam pipeline after 240 000 h of operation under creep conditions in the form of the relation $\log t_{re} = f(T_b)$ at σ_b = 55 MPa

TABLE 4

Test results of short creep tests at a constant test stress level and for different levels of temperature higher than the expected operating temperature

Steel grade	Tested material			Test stress σ_b [MPa]	Test temperature T_b [°C]				
	Dimensions $D_z \times g_n$ [mm]	Operating parameters			620	640	660	680	700
		Pressure p_r [MPa]	Temp. t_r [°C]		Time to rupture t_z [h]				
secondary steam pipeline 10CrMo9-10 after 240 000 h	508×16	3.0	540	55	(2000)	956	480	139	31
welded joint 10CrMo91-0 after 240 000 h					2023	688	166	75	20
secondary steam pipeline 10CrMo9-10 after 280 000 h					2168	980	250	81	31
welded joint 10CrMo91-0 after 280 000 h					1612	680	221	77	24
secondary steam pipeline 10CrMo9-10 after 308 000 h					2058	1135	316	128	38
welded joint 10CrMo91-0 after 308 000 h					1612	551	210	71	26

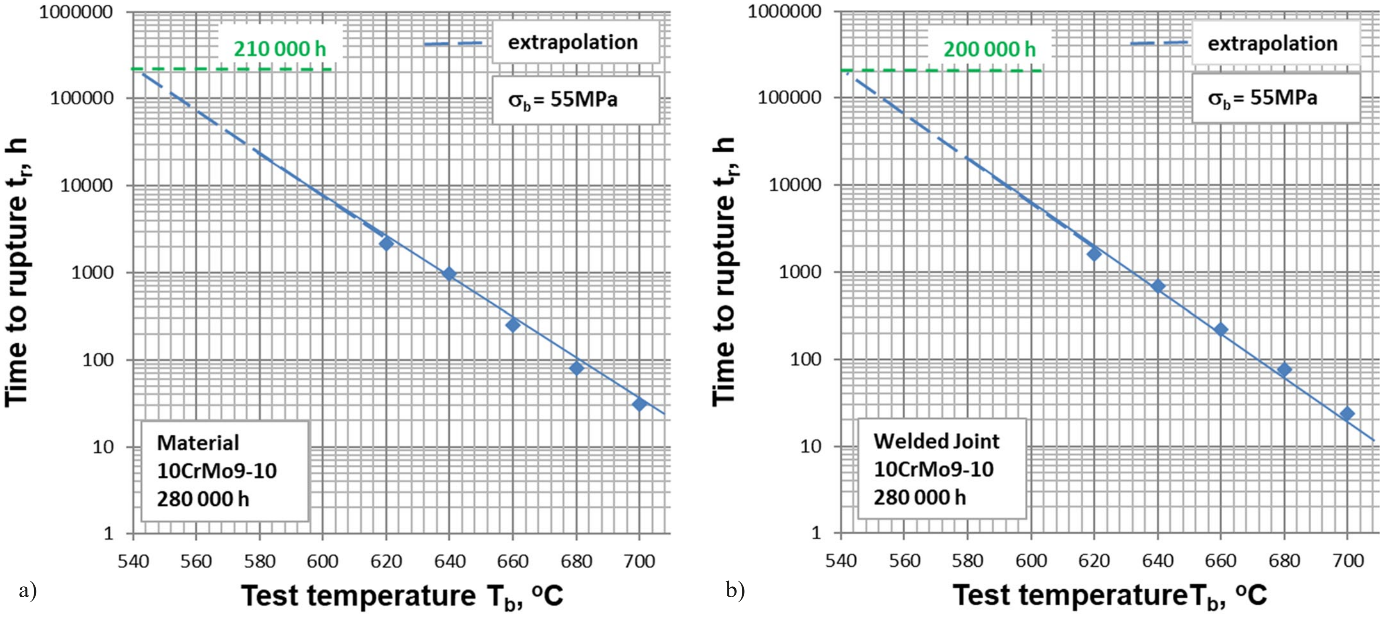

Fig. 8. Results of short creep tests of welded joint materials of the secondary steam pipeline after 280 000 h of operation under creep conditions in the form of the relation $\log t_{re} = f(T_b)$) at σ_b = 55 MPa

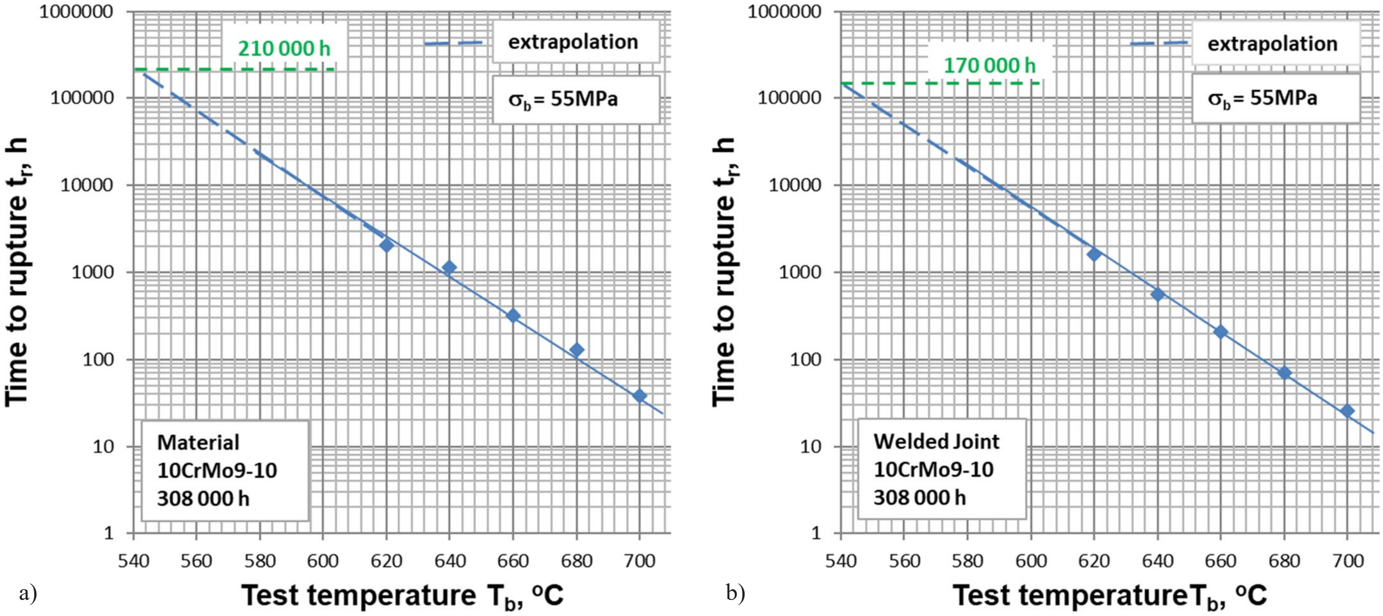

Fig. 9. Results of short creep tests of welded joint materials of the secondary steam pipeline after 308 000 h of operation under creep conditions in the form of the relation $\log t_{re} = f(T_b)$) at σ_b = 55 MPa

TABLE 5

Residual and disposable residual based on abbreviated creep tests of base materials and welded joints

Service time [h]	Steel grade	Tested material		Test stress σ_r [MPa]	Assumed temperature for further operation T_r [°C]	Estimated durability, [h][1)]	
		Tested sections designation	Dimensions $D_z \times g_n$ [mm]			residual t_{re}	disposable residual, t_b
240 000	10CrMo9-10	base material	508×16	55	540	280 000	168 000
		welded joint				210 000	126 000
280 000		base material				210 000	126 000
		welded joint				200 000	120 000
308 000		base material				210 000	126 000
		welded joint				170 000	102 000

Note: [1)] Provided that the amount of permanent deformation after the previous long-term operation does not exceed max. 1%

Based on the completed creep tests, the residual life was determined using the extrapolation method and the available residual life was estimated, which is the safe period of further operation for the operating parameters of stress σ_r and temperature T_r. The obtained extrapolation results based on creep tests are summarized in TABLE 5.

4. Results and discussion

Tensile strength results of the secondary steam pipelines tested elements after approximately 240 000, 280 000 and 308 000 h of service under creep conditions show that the base material and the welded joint meet the requirements of tensile strength at room temperature R_m for 10CrMo9-10 steel after normalizing and tempering according to PN-74/H-74252;

The yield stress results after 240 000 h and 308 000 h show that the base material and the welded joint meet the requirements of the minimum yield stress at room temperature $R_{e\,\min}$ for 10CrMo9-10 steel after normalizing and tempering according to PN-74/H-74252. After 280 000 h, the base material meets the requirements of the minimum yield stress at room temperature, but the welded joint does not meet this requirement.

Regarding the elongation (A_5) results, for samples after 240 000, 280 000 and 308 000 h of service under creep conditions, the base material and the welded joint meet the requirements of min – elongation values.

The R_e^t results for the 240 000 h and 280 000 h of base material meet the minimum yield strength requirements at temperatures of 200, 300, 400, 450, and 500°C, while the welded joint meets the above requirement at all temperatures apart from 200°C. For base material and welded joint after 308 000 h, it meets minimum yield strength requirements at all temperature ranges.

The fracture appearance transition temperature (FATT50) for the secondary steam pipeline material after 240 000 h of operation is around –50°C, and for the weld material of the welded joint, it is approximately –15°C. However, for the base material and the weld of the peripheral welded joint after 280 000 h of operation, it is approximate –5°C. In turn, for the secondary steam pipeline material after 308 000 h of operation, it is approximately –25°C.

Compared to the as-delivered state, the fracture appearance transition temperature (FATT50) for most materials of the tested elements is shifted to higher values. Only in a few cases, after long-term operation under creep conditions, is the material characterized by an impact strength level higher than the minimum required for the material in the metallurgical delivery condition. The impact strength value depends not only on the development of precipitation processes resulting from creep but also on the development of internal damage and structural discontinuities occurring during operation [1-4,7].

It can, therefore, be concluded that the impact strength testing method for materials after creep service is not directly useful for assessing residual durability and determining the degree of exhaustion. However, it is useful for assessing the material's ability to transfer loads related to pressure tests and shutdowns and starts of installations during their further operation [1,2,5,8].

The secondary steam pipeline material made of 10CrMo9-10 steel after 240 000 h, 280 000 h and 308 000 h of operation, respectively, meets the minimum limit value of 27 J at room temperature for all elements of the tested welded joints (TABLE 3).

The determined residual durability (t_{re}) for the material and welded joint of the secondary steam pipeline made of 10CrMo9-10 steel after 240 000 h of operation is 280 and 210 thousand hours, respectively, and the estimated residual creep strength tb is 168, 126 thousand hours, respectively. The determined residual durability of the material after 280 000 h of operation is 210 and 200 thousand hours, respectively, and the estimated residual creep strength tb is 126 and 120 thousand hours, respectively. For the secondary steam pipeline after 308 000 h of operation, the determined residual durability of the material and welded joint is 210 000 and 170 000 h, respectively, and the estimated residual creep strength tb is 126 000 and 102 000 h, respectively.

5. Conclusions

Based on the research conducted, it can be concluded that for the base material and welded joint of the secondary steam pipeline made of 10CrM09-10 steel, after 240 000, 280 000, and 308 000 h of operation under creep conditions, the tensile strength requirements at room temperature according to the requirements of the standards for steel products are met.

- For all tested materials, the obtained yield strength values at room temperature and at 500°C close to the operating temperature are higher than the minimum required for the tested steel in its initial state, except the welded joint of the secondary steam pipeline after 280 000 h of operation.
- The brittle transition temperature of the tested welded joint elements of the secondary steam pipeline after 240 000, 280 000 and 308 000 h of operation is negative. The impact strength of the material and the welded joint for all tested pipelines is higher than the value taken for the brittle transition temperature (27 J). No significant reduction in the impact strength depending on the operation time was observed either.
- The tested material with mechanical properties greater than those required for the initial state can carry operating loads for temperature and stress parameters lower or/and equal to the calculated ones, of course, in connection with the state of the structure and its corresponding degree of exhaustion [1,7]. For this reason, it will be necessary to carry out microstructural evolution of the tested secondary steam pipelines after 240 000, 280 000 and 308 000 h of operation in creep conditions.
- The estimated residual life and disposable residual life of all tested pipelines for the welded joint are lower than for the base material.

- The estimated residual life and disposable residual life are the lowest for the material and welded joint after 308 000 h of operation and the highest for the joint after 240 000 h. A decrease in the residual life and disposable residual life was observed with the extension of the operating time of the tested pipelines.

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