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The evaluation of suitability for operation of low-alloy Cr-Mo and Cr-Mo-V steel welded joints beyond the design work time

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ABSTRACT

Purpose: The purpose of this paper was to develop material characteristics for homogeneous circumferential welded joints in low-alloy steel steam pipelines of power units after long-term service beyond the design work time.

Design/methodology/approach: The investigations of microstructure using scanning microscopy, investigations of mechanical properties at room and elevated temperature, in particular the static tensile test, determination of brittle fracture appearance transition temperature based on the impact strength tests and abridged creep tests without measurement of elongation during test were carried out in order to determine the residual life of the material.

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

Practical implications: The applied methodology and adopted procedures will be used for evaluation of condition and prediction about further operation of welded joints of elements in the pressure part of power equipment working under creep conditions.

Originality/value: The obtained results of investigations will be the elements of material characteristics developed by the Institute for Ferrous Metallurgy for steels and welded joints made from them working under creep conditions.

Keywords: Mechanical properties; Structure; Degradation after creep service; Residual life; Steel 14MoV63; Steel 13CrMo4-5

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PROPERTIES

1. Introduction

In the evaluation of the degradation of critical elements of power units after long-term service under creep conditions working above 150 000 hours and in order to determine their suitability for further operation, the comprehensive tests the selection of which depends on, but is not limited to, the type and working conditions of the analysed structural component as well as its accessibility are required. In the evaluation of structural components working under creep conditions, the condition assessment of their material as well as HAZ material and welds in the used welded joints is necessary [3-8]. To estimate and determine the time of safe operation for the material of critical elements of power units working under creep conditions, particularly when the design work time has been exceeded, the knowledge of their residual creep strength is necessary. For the materials of welded joints the abridged creep tests without measurement of elongation during test were carried out to determine creep strength characteristics for the material of circumferential welded joints made from low-alloy steels. Based on the abridged creep tests using the Larson-Miller parametric relationship, the residual creep strength characteristics will be determined. These characteristics should allow good estimation of residual life and disposable residual life for various levels of working stresses σ_r within the range of working temperatures T_r. The knowledge of the ability to transfer the loads of material and welded joints due to periodical shutdowns and start-ups of the boiler connected with periodical inspections and repairs as well as failures, and also with water pressure tests is essential too. Therefore, apart from residual creep strength, the knowledge of the basic strength and plastic properties in connection with the image of the elements of welded joints after long-term service under creep conditions is also important [9-16].

2. Material for investigations

The material for investigations included the test specimens of selected elements in the pressure part of boilers with homogeneous circumferential welded joints from 14MoV6-3 and 10CrMo9-10 pursuant to PN-75/H-84024 low-alloy steel after long-term service under creep conditions much beyond the assumed time. The summary of materials for investigations is presented in Fig. 1.

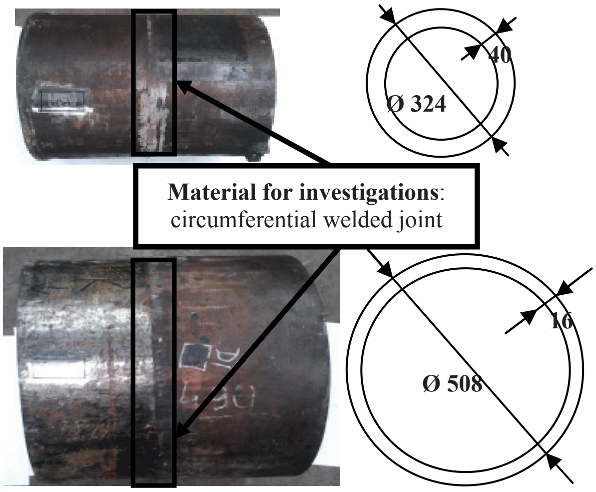

Fig. 1. Material for investigations in the form of homogeneous circumferential welded joint after 240 000 h service under creep conditions: a) primary steam pipeline from 14MoV63 steel (marked 1); b) secondary steam pipeline 10CrMo9-10 (marked 2)

Chemical composition of the materials of tested specimens of the primary and secondary steam pipelines with reference to the requirements of the standard specification is presented in Table 1. The results of check analysis of chemical composition revealed that the materials of tested specimens from critical elements in the pressure parts of power units after long-term service under creep conditions met the requirements of the standard with regard to chemical composition of tested 14MoV6-3 and 10CrMo9-10 steels.

3. Range of investigations

At specific points within the material from the acquired specimens for investigations, the following non-destructive tests were carried out: mechanical testing, microstructure investigation and creep strength tests. Based on the obtained test results the material condition assessment is made and the creep strength, which is the residual creep strength, is determined for working parameters of further operation (temperature and stress). By knowing the residual creep strength for parameters of further operation, the disposable residual life can be determined, which is the expected time of further safe service for the adopted working parameters.

Table 1.
Chemical composition of the material of tested specimens after long-term service under creep conditions

Grade of material	Content of elements, %								
	C	**Mn**	**Si**	**P**	**S**	**Cu**	**Cr**	**Ni**	**Mo**	**others**
PN-75/H-84024 14MoV6-3 (13HMF)	**0.10 0.18**	**0.40 0.70**	**0.15 0.35**	**max 0.04**	**max 0.04**	**max 0.25**	**0.30 0.60**	**max 0.30**	**0.50 0.65**	**V 0.22-0.35 Al max 0.02**
14MoV6-3 (13HMF) after 240 000 h **marked 1**	0.12	0.41	0.27	0.015	0.020	0.088	0.45	0.075	0.52	V 0.28
Grade of material	**C**	**Mn**	**Si**	**P**	**S**	**Cu**	**Cr**	**Ni**	**Mo**	**others**
PN-75/H-84024 10CrMo9-10 (10H2M)	**0.08 0.15**	**0.40 0.60**	**0.15 0.50**	**max 0.03**	**max 0.03**	**max 0.25**	**2.00 2.50**	**max 0.30**	**0.90 1.10**	**Al max 0.020**
10CrMo9-10 (10H2M) after 240 000 h **marked 2**	0.082	0.42	0.28	0.007	0.015	0.074	2.25	0.089	1.01	Al 0.007

4. Test results

4.1. Evaluation of mechanical properties and structure of the material

Evaluation of mechanical properties

The investigations of strength properties were carried out as a part of the tensile test at room temperature and at elevated temperature similar to the real operating temperature. The obtained results of the tensile strength (TS) and yield point (YP) tests are shown in Fig. 2a, while the results of impact energy tests, carried out on longitudinal test pieces with V notches cut perpendicularly to the surface of tested pipes – in Fig. 2b. The impact energy tests were carried out at temperature levels selected so that the brittle fracture appearance transition temperature can be determined for the material of tested elements.

Investigations of microstructure

The investigations of microstructure were carried out on microsections following grinding, polishing and etching. The observations were conducted using Inspect F scanning electron microscope with magnifications of 500, 1000, 2000 and 5000x. The results of the investigations in the form of material structure images are presented in Fig. 3.

a)

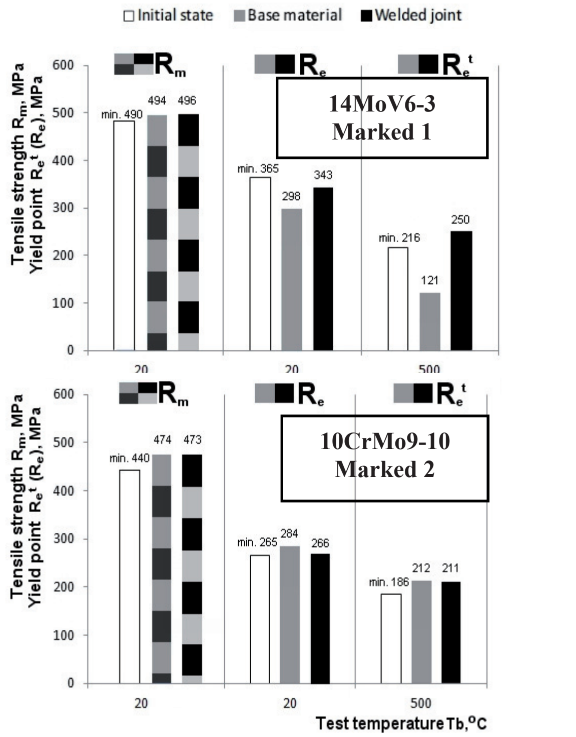

Fig. 2. Results of mechanical testing of the material of tested specimens with homogeneous circumferential welded joint after 240 000 h service under creep conditions: a) tensile strength and yield point at room and elevated temperature

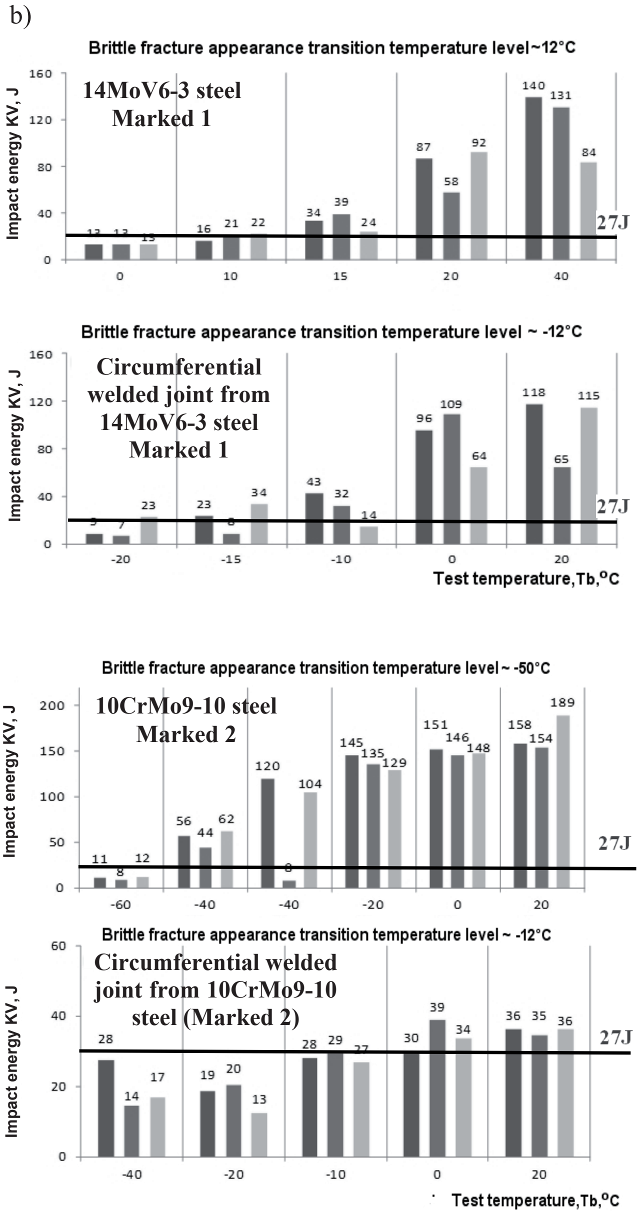

Fig. 2. Results of mechanical testing of the material of tested specimens with homogeneous circumferential welded joint after 240 000 h service under creep conditions: b) impact energy at different test temperature levels for 14MoV6-3 steel primary steam pipeline (marked 1) and 10CrMo9-10 steel secondary steam pipeline (marked 2)

The description of microstructure including the review of results and exhaustion extent t_e/t_r estimated based on proprietary classification of the Institute for Ferrous Metallurgy is provided in Table 2.

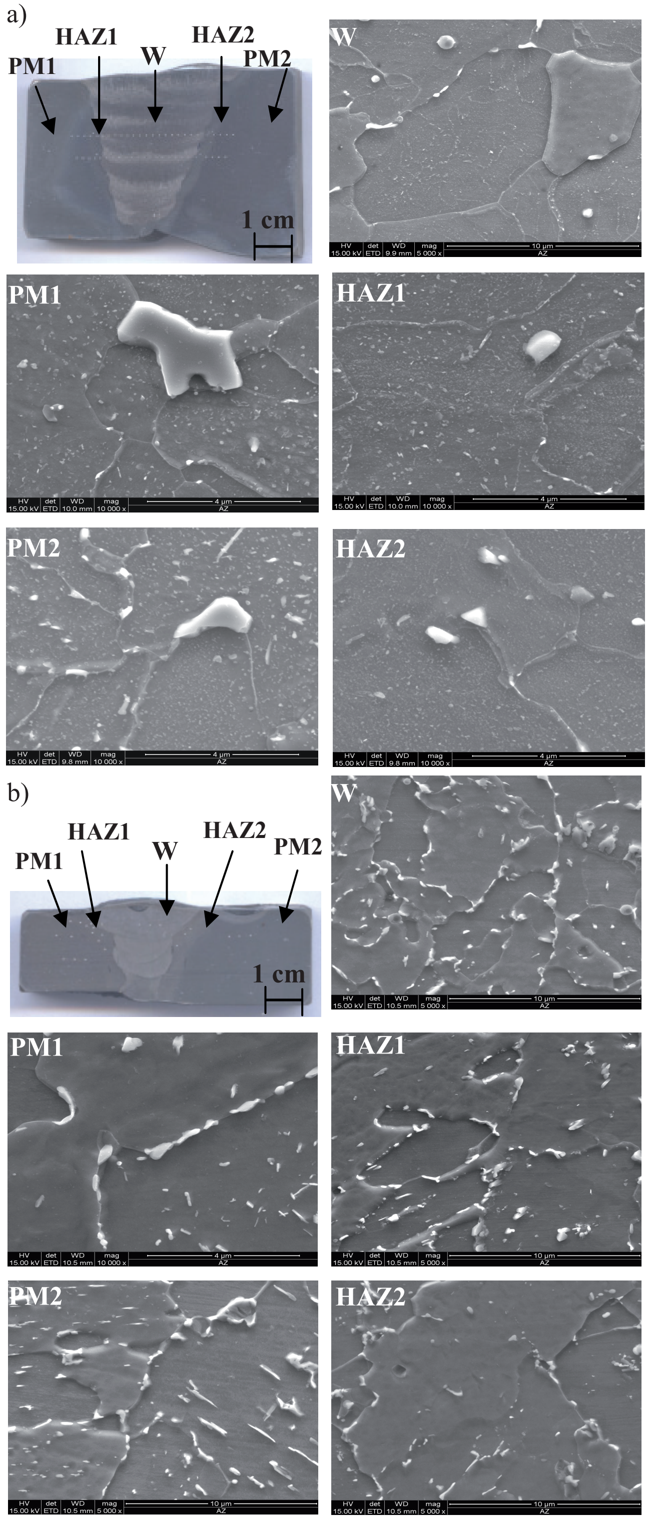

Fig. 3. Comparison of microstructure of the elements of welded joint: MR, HAZ and SP of: a) 14MoV63 primary steam pipeline (marked 1); b) 10CrMo9-10 secondary steam pipeline (marked 2); SEM

Table 2.
Review of the results of investigations of microstructure of the elements of homogeneous circumferential welded joint after 240 000 h service under creep conditions

Material for investigations		Description of microstructure Material condition – exhaustion extent	Hardness HV10
Element: Primary steam pipeline **Grade:** 14MoV6-3 (13HMF) **Service time:** 240 000 h service **designation ZGP1**	PM	Ferritic-bainitic structure. Partially coagulated bainitic areas. At the ferrite grain boundaries, there are precipitates of different size, mostly fine. Inside the ferrite grains, there are very fine evenly distributed precipitates. No discontinuities and micro-cracks are observed in the structure. No initiation of damaging processes is observed. Bainitic areas: class I, precipitates: class a Damaging processes: class O **CLASS 1/2, EXHAUSTION EXTENT: approx. 0.3**	156
	HAZ	Heat-affected zone structure. No discontinuities and micro-cracks are found in the structure.	191
	W	Structure of weld material in welded joint. No discontinuities and micro-cracks are found in the structure.	189
Element: Secondary steam pipeline **Grade:** 10CrMo9-10 (10H2M) **Service time:** 240 000 h service **designation ZGP1**	PM	Ferritic-bainitic structure. Partially coagulated bainitic areas. At the ferrite grain boundaries, there are precipitates, some of rather significant size, forming chains in places. Inside the ferrite grains, there are numerous, mostly fine, precipitates. No discontinuities and micro-cracks are observed in the structure. No initiation of damaging processes is observed. Bainitic areas: class I, precipitates: class a Damaging processes: class O **CLASS 1/2, EXHAUSTION EXTENT: approx. 0.3**	149
	HAZ	Heat-affected zone structure. No discontinuities and micro-cracks are found in the structure.	172
	W	Structure of weld material in welded joint. No discontinuities and micro-cracks found in the structure.	201

Abridged creep tests

To reduce the time of creep tests and evaluation of residual life, the abridged creep tests of a few dozen to max 3 to 5 thousand hours were used. This makes it possible to obtain test results within maximum several months, yielding good estimation of residual life. The acceleration of the creep process and reduction in the time of testing is obtained in creep tests carried out at uniaxial tension on test pieces taken from the tested material by conducting the tests [1,2]:

- at constant test stress corresponding to the operating one and at different levels of test temperature, much higher than the operating one,
- at constant test temperature corresponding to the operating one and at different levels of test stress, much higher than the operating ones.

High concurrence of results obtained in abridged creep tests conducted at a constant stress corresponding to the operating one and in long-term creep tests conducted as a part of in-house investigations carried out at the Institute for Ferrous Metallurgy verified this method positively and allowed its use in the engineering practice.

Therefore, the abridged creep tests were carried out for the tested materials and welded joints made from them. The tests were carried out at constant test stress level corresponding to the operating one $\sigma_b = \sigma_r$ =const and at constant test temperature T_b for each of the tests, but with different values ranging between 620ºC and 700ºC in 20ºC steps. The test results are presented in the form of relationship log $t_r = f(T_b)$ at σ_b = const, where t_r is the time to rupture in creep test. They allow the straight line inclined towards the time to rupture t_r axis to be outlined. The residual life is determined by extrapolation of the obtained line towards the lower temperature corresponding to the operating one T_e.

The obtained results of abridged creep tests for the material of pipeline and circumferential welded joint in the tested specimen of 14MoV6-3 steel primary steam pipeline (marked 1) after 240 000 h service under creep conditions conducted at constant stress level σ_b = 60 MPa, corresponding to the assumed working stress σ_r of further operation, are presented in the form of relationship $t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ in Fig. 4 and summarised in Table 3, while the obtained results of abridged creep tests for the material of pipeline and circumferential welded joint in the tested specimen of 10CrMo9-10 steel secondary steam pipeline (marked 2) after 240 000 h service under creep conditions conducted at constant test stress level σ_b = 55 MPa, corresponding to the assumed working stress σ_r of further operation, are presented in the form of relationship $t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ in Fig. 5 and summarised in Table 3.

a) b)

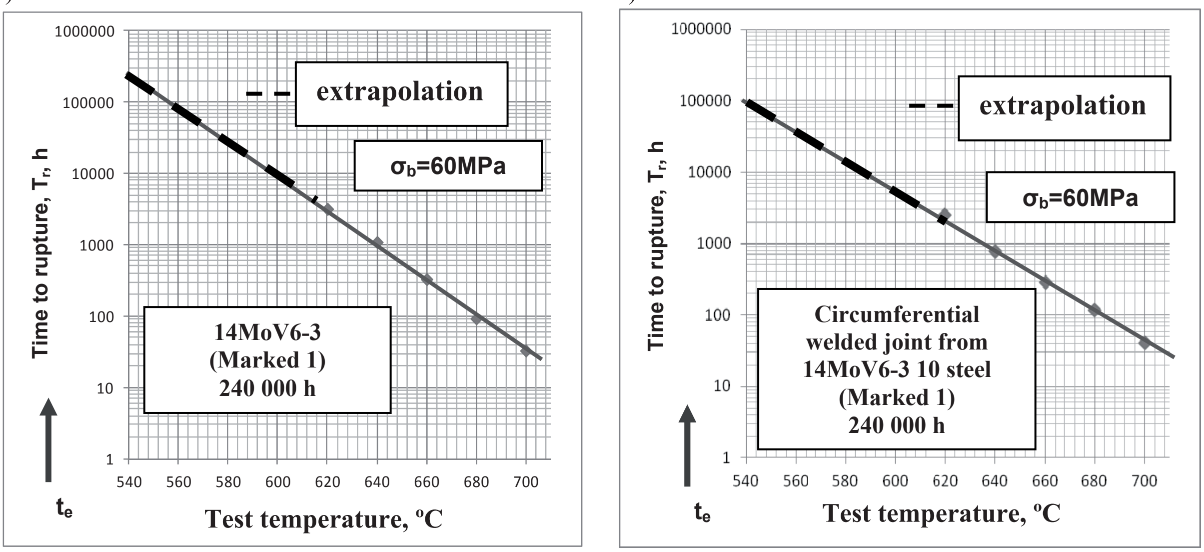

Fig. 4. Results of abridged creep tests of: a) pipeline material; b) circumferential welded joint of the 14MoV6-3 (13HMF) steel primary steam pipeline after 240 000 h service under creep conditions, as relationship $logt_{re}=f(T_b)$ at σ_b=60MPa

a) b)

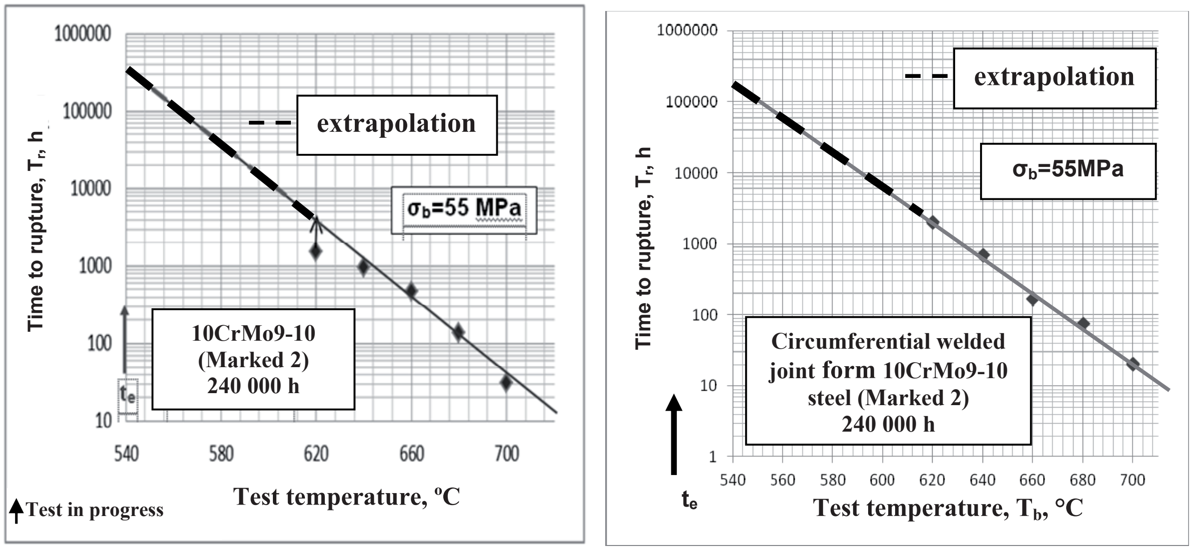

Fig. 5. Results of abridged creep tests of: a) pipeline materials; b) circumferential welded joint of the 10CrMo9-10 (10H2M) secondary steam pipeline after 240 000 h service under creep conditions, as relationship $logt_{re}=f(T_b)$ at σ_b=55MPa

Table 3.
Results of abridged creep tests at constant test stress level and for different levels of temperature higher than the expected operating one for the material of circumferential welded joint of the specimen of the main 14MoV6-3 steel primary steam pipeline (marked 1) and 10CrMo9-10 steel secondary steam pipeline (marked 2) after 240 000 h service

Steel grade specimen design	Material for investigations			Test stress σ_b, MPa	Test temperature T_b, °C				
	Dim.	Working parameters			620	640	660	680	700
	D_z x g_n, mm	Press. p_r, MPa	Temp. t_r, °C		Time to rupture t_z, h				
1	2	3	4	5	6	7	8	9	10
Parent material 14MoV6-3 (13HMF) **Marked 1**	324x40	14.0	540	60	3197	1096	331	93	33
Welded joint of the primary steam pipeline 14MoV6-3 (13HMF) **Marked 1**					2495	782	288	116	41
Parent material 10CrMo9-10 (10H2M) **Marked 2**	508x16	3.0	540	55	(1500)	956	480	139	31
Welded joint of the secondary steam pipeline 10CrMo9-10 (10H2M) **Marked 2**					2023	688	166	75	20

Based on the completed abridged creep tests and applied extrapolation method, the residual life was determined and the disposable residual life, which is the time of further safe service for the working parameters of stress σ_r and temperature T_r, was evaluated. The obtained results of extrapolation based on creep tests are summarised in Table 4.

4.2. Material condition assessment and determination of residual life – discussion of the results

The condition assessment of the material of tested circumferential welded joints of the main 14MoV6-3 steel primary steam pipeline (marked 1) and 10CrMo9-10 steel secondary steam pipeline (marked 2) after 240 000 h service was made based on joint assessment of the obtained results of mechanical testing, structure investigation and residual creep strength test.

For the 14MoV6-3 steel primary steam pipeline after 240 000 h service, the requirements for yield point at room temperature for both the parent material and welded joint and the requirements with regard to yield point at a temperature similar to the operating one for the parent material are not met. Also, the brittle fracture appearance transition temperature for the parent material of the tested 14MoV6-3 steel pipeline is positive and equals to +12°C.

For the 10CrMo9-10 steel secondary steam pipeline after 240 000 h service the requirement for tensile strength at room temperature R_m, yield point at room temperature $R_{e\,min}$ and min. yield point R_e^t at a temperature similar to the operating one is met. Also, the brittle fracture appearance transition temperature for both the parent material and the circumferential welded joint is negative.

Table 4.
Residual life and disposable residual life based on abridged creep tests of the materials of tested circumferential welded joints of the main 14MoV6-3 steel primary steam pipeline (marked 1) and 10CrMo9-10 steel secondary steam pipeline (marked 2) after 240 000 h service

No.	Steel grade specimen designation	Material for investigations		Assumed operating stress σ_r, MPa	Assumed temperature of further operation T_r, °C	Estimated life time, h [1)]	
		Element of the joint	Dim. $D_z x g_n$, mm			residual t_{re}	disposable residual t_b
1	2	3	4	5	6	7	8
1	14MoV6-3 (13HMF) **Marked 1**	Parent material	324x40	60	540	200 000	110 000
		Welded joint of the primary steam pipeline				100 000	55 000
2	10CrMo9-10 (10H2M) **Marked 2**	Parent material		55	540	300 000	165 000
		Welded joint of the secondary steam pipeline	508x16			200 000	110 000

Note: [1.)] Provided that plastic strain after the current long-term service does not exceed max 1%

The above-mentioned information is necessary to take a decision in the event when pressure test is required. This test must then take into consideration the level of these properties in the selection of water pressure test parameters. This can only be the leak proof test of the pipeline, not the strength test. As the brittle fracture appearance transition temperature of parent material of the 14MoV6-3 (13HMF) steel primary steam pipeline after 240 000 h service is positive, the required boiler start-up and shutdown conditions should be followed absolutely.

The obtained results of mechanical testing in combination with the results of structure investigations for the primary and secondary steam pipeline show slight wear-out of the tested material the exhaustion extent t_e/t_r of which was estimated to be approx. 0.3.

Also, hardness of tested elements of the circumferential welded joints for critical elements in the pressure part of power units is much lower than the maximum admissible hardness of 350 HV, ranging between approx. 156 and approx. 191 HV10 for the 14MoV63 steel primary steam pipeline, while for the 10CrMo9-10 steel secondary steam pipeline it ranges between approx. 149 and approx. 201 HV10. The course of changes in hardness at the transition through individual zones of the joints is mild. This allows to judge that the tested welded joints will be able to transfer the required considerable loads, including those that occur during water pressure tests, shutdowns and start-ups.

The numerical dimension of this suitability is obtained by extrapolating the straight line obtained based on abridged creep tests from the relationship $\log t_r = f(T_b)$ at σ_b=const towards the lower temperature, which allows the residual life t_{re} to be determined for temperature corresponding to the operating one.

The abridged creep tests of circumferential welded joint of the 14MoV6-3 steel primary steam pipeline and the 10CrMo9-10 steel secondary steam pipeline after 240 000 h service carried out at constant test stress, σ_b = const, allowed the residual life to be determined and the disposable residual life to be evaluated for the expected operating temperature of 540°C. The residual life t_{re} determined for the material of pipeline and circumferential welded joint of the 14MoV6-3 steel primary steam pipeline after 240 000 h service is 200 thousand hours and 100 thousand hours, respectively, and the estimated residual creep strength t_b is 110 thousand hours and 55 thousand hours, respectively, while the residual life t_{re} determined for the material of pipeline and circumferential welded joint of the 10CrMo9-10 steel secondary steam pipeline after 240 000 h service is 300 thousand hours and 200 thousand hours, respectively, and the estimated residual creep strength t_b is 165 thousand hours and 110 thousand hours, respectively.

5. Summary

The obtained results of investigations are the elements of material characteristics developed by the Institute for Ferrous Metallurgy for steels working under creep conditions. These characteristics are used in condition assessment and forecasting about further safe service for the parent material and welded joint operated beyond the design time. Moreover, they are useful in taking decisions on the possibility to make welded joints containing materials after long-term service under creep conditions and development of technologies for their production.

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