Archives of Materials Science and Engineering

Volume 68
Issue 1
July 2014
Pages 36-44

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

The impact of repair welded joint on the life of Cr-Mo-V steel steam pipeline after service under creep conditions

A. Zieliński [a,*], M. Dziuba-Kałuża [a], J. Dobrzański [a], M. Sroka [b]

[a] Institute for Ferrous Metallurgy, ul. K. Miarki 12, 44-100 Gliwice, Poland

[b] Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland

* Corresponding e-mail address: azielinski@imz.pl

Received 19.04.2014; published in revised form 01.07.2014

ABSTRACT

Purpose: The purpose of this paper was to examine the impact of repair welded joints on the life time of primary steam pipelines after more than 200 000 h service under creep conditions.

Design/methodology/approach: The investigations of microstructure using scanning microscopy, investigations of mechanical properties at room and elevated temperature, determination of brittle fracture appearance transition temperature based on impact strength tests and abridged creep tests were carried out in order to determine the residual life of the material.

Findings: The completed investigations allowed the time of further safe operation of the elements of primary steam pipeline with repair welded joint to be determined in relation to the parent material and welded joint after service.

Practical implications: The assessment of residual life and disposable residual life, and thus the estimation or determination of possible time of further safe operation, is of the essence in case of operating the elements much beyond the design work time.

Originality/value: The obtained results of investigations are 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: Creep; Diagnostics of materials; Welded joints after service; Cr-Mo-V steel; Residual life

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

A. Zieliński, M. Dziuba-Kałuża, J. Dobrzański, M. Sroka, The impact of repair welded joint on the life of Cr-Mo-V steel steam pipeline after service under creep conditions, Archives of Materials Science and Engineering 68/1 (2014) 36-44.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The energy sector in Poland is considerably obsolete. Eighty percent of power units have exceeded the design work time of 100 000 hours – mostly twice, and approx. forty percent of them is 35 years old, ten percent have reached the age of 50 – which is near to technical death, and the new constructed power units are occasional and do not provide the energy security of Poland in the years to come [1]. Therefore, the main efforts aimed at keeping the electric energy production level are directed at the extension of operation much beyond the design work time with simultaneous modernisation of boilers and turbines to improve the technical and economical indicators (increase in power and improvement in efficiency and availability), increase in the life time, and above all reduction in the emission of harmful pollutants to the atmosphere, water and soil.

The above-mentioned unplanned operation of power boilers working in Poland for more than 200 000 hours and up to 350 000 hours requires a new approach to the development of procedures for diagnostics of these materials. A particularly important issue with regard to ensuring a failure-free operation is strength of welded joints of the elements of steam pipelines working under creep conditions [2]. The example which is the basis for undertaking the research on solution to this problem is the intensification of degradation of the material of critical elements and their welded joints (parent material, HAZ, weld) observed in recent years [3]. A very important issue is to develop methods for assessment of the condition and suitability of materials for further operation, suitability of these materials for being joined by welding and suitability of the repair welded joints for operation under creep conditions [4].

The evaluation of degradation of the elements of power systems after long-term service under creep conditions and the determination of their suitability for further operation requires the comprehensive tests and measurements 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 [5,6].

To estimate and determine the time of safe operation for the material of pipelines working under creep conditions, particularly after the design work time has been exceeded, the knowledge of their residual creep strength is necessary. As each system must be shut down from time to time (planned and unplanned shutdowns) to perform periodic repairs, it is necessary to perform water pressure tests to check the system for leaktightness and its ability to transfer loads at the test temperature. Therefore, apart from residual creep strength, the knowledge of the basic strength and plastic properties of these materials after long-term service in different times is also important.

In most diagnostic works, the investigations of steam pipeline welded joints are based on non-destructive magnetic particle investigations, aimed at revealing the existence of micro-cracks, and to a lesser extent on structure examinations using the light microscopy. It needs to be emphasised that magnetic particle investigations are one of the elements of non-destructive testing of welded joints and they do not provide information on the state and degree of material degradation, whereas the structure observation using light microscope can only be applied to the assessment of metallographic microsection for correct preparation. In order to properly evaluate material condition, i.e. the exhaustion extent, based on changes in the structure of analysed material, such tests should be performed using scanning electron microscopy with magnifications of up to 5 000x and suitable resolution of obtained structure images [7]. To evaluate the exhaustion extent of tested materials, the database in the form of materials characteristics of changes in the level of mechanical properties and residual creep strength in relation to structure condition is required. It concerns not only the diagnostics of welded joints after long-term service, but above all the assessment of behaviour of the material of repair welded joints for materials in initial state with material after long-term service [8-19].

The purpose of this paper was to determine the time of safe operation for both the welded joints after long-term operation and the repair welded joints made during, but not limited to, the modernisation works on steam pipelines, particularly those working after having exceeded the design work time significantly.

The results of investigations presented below are a part of the project: “Methodology, assessment and forecast about the operation of welded joints in pressure elements of power boilers beyond the design work time”.

2. Material for investigations

The material for investigations included the specimen of primary steam pipeline with circumferential welded joint after 218 000 h service under creep conditions, i.e. at 540°C and 14 MPa. In addition, the “repair” welded joint was made on the acquired specimen under industrial conditions to simulate steam pipeline repairs made by welding. The above-mentioned procedure allowed the tests and their analysis to be performed for parent material, welded joint after long-term service and repair welded joint.

3. Research methodology

The investigations of mechanical properties included the static tensile test at room and elevated temperature using Zwick testing machine with max stress of 200 kN, hardness measurement by Vickers method with Future – Tech FM – 7 hardness testing machine using the indenter load of 10 kG and impact test on standard V-notched test samples. The microstructural investigations were carried out with Inspect F scanning electron microscope (SEM) on conventionally prepared etched metallographic microsections. The analysis of precipitation processes was carried out by X-ray analysis of carbide isolates with Philips diffractometer. The abridged creep tests at a temperature higher than the operating one and at stress similar to the operating one were carried out on Instron single-sample machines with temperature accuracy during the test of ±1°C.

4. Test results

Chemical composition of the material of tested primary steam pipeline specimen with reference to the requirements of standard specification is presented in Table 1 [20]. The results of check analysis of chemical composition revealed that the material of tested specimen of critical element 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 13HMF (14MoV63) steel.

Table 1.
Chemical composition of tested primary steam pipeline

	Content of elements, % – steel 13HMF						
	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	0.15	0.26	0.52	0.51	0.59	0.16	0.29

Hardness measurements of the material of steam pipeline jacket, material of the elements of circumferential welded joint of primary steam pipeline after 218 000 h service and repair circumferential welded joint made from materials after 218 000 h service were taken on transverse metallographic microsections. The results of hardness measurements for the circumferential welded joint after 218 000 h service and the new repair welded joint made from materials after 218 000 h service are shown in Fig. 1.

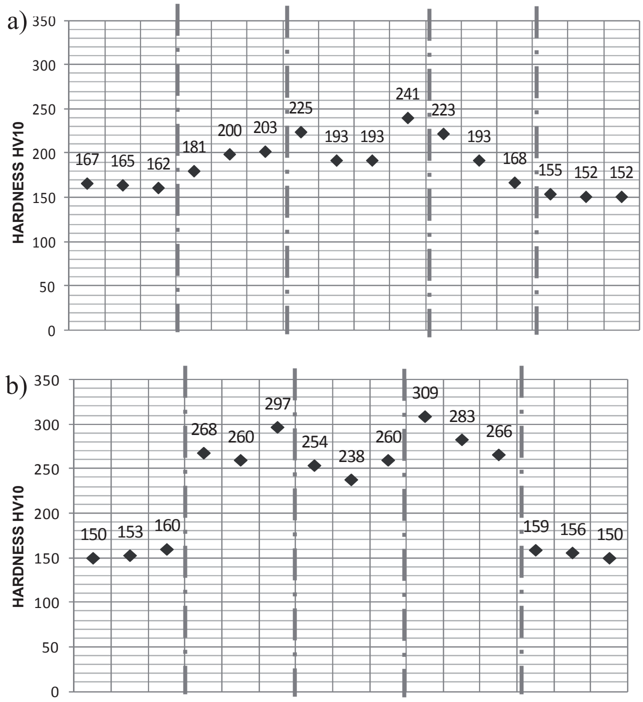

Fig. 1. Hardness measurement results for: a) circumferential welded joint from 13HMF steel after service; b) new repair circumferential welded joint from 13HMF steel

For the elements of circumferential welded joint after 218 h service the hardness measurements revealed no sudden changes during the transition through individual joint zones in contrast with the elements of repair circumferential welded joint from materials after 218 000 h service. Hardness for the circumferential joint after long-term service, from parent material through HAZ, weld, HAZ up to parent material, differs by approx. 90 units at the most and does not exceed 260 HV10, while for the new repair welded joint from materials after long-term service it is lower than the maximum admissible hardness of 350 HV10, ranging between approx. 150 and approx. 309 HV10 for the 13HMF steel primary steam pipeline.

The microstructural investigations were performed on metallographic microsections using scanning electron microscope with magnifications of 500, 1000, 2000 and 5000x. The test results in the form of structure images are shown in Fig. 2 for the parent material of primary steam pipeline after 218 000 h service, in Fig. 3 for the elements of circumferential welded joint after 218 000 h service and in Fig. 4 for the elements of new repair welded joint. The description of microstructure including the exhaustion extent t_e/t_r estimated based on the proprietary classification of the Institute for Ferrous Metallurgy for the parent material and the elements of tested welded joints of primary steam pipeline is summarised in Table 2.

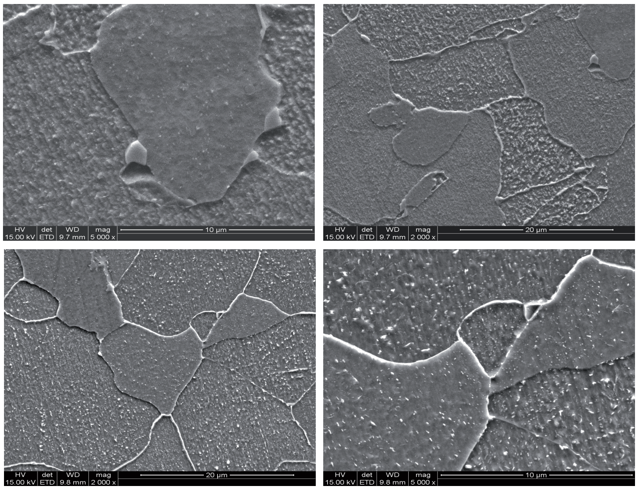

Fig. 2. Images of structure elements of the material of jacket of the 13HMF steel primary steam pipeline specimen after 218 000 h service (SEM), transverse microsection

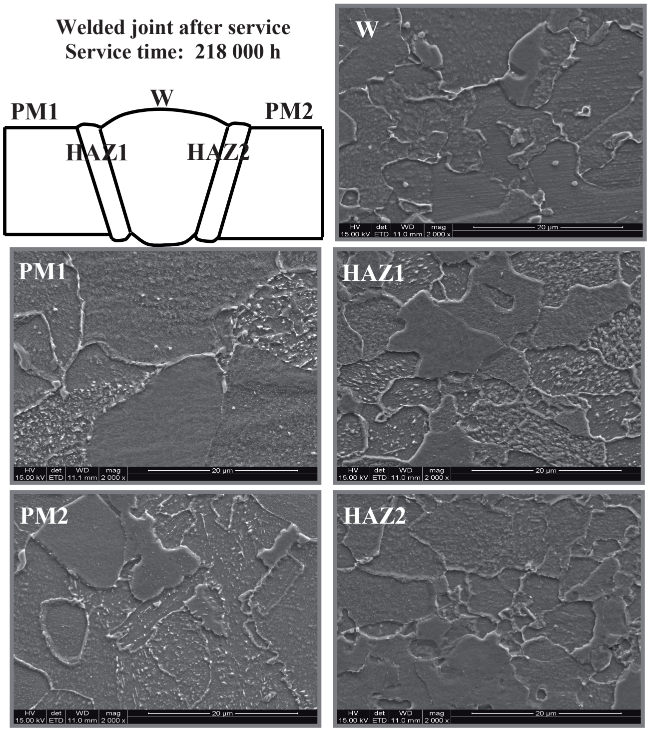

Fig. 3. Structure of the material of elements of tested 13HMF steel welded joint after 218 000 h service under creep conditions, microstructure testing area: parent material marked MR1, MR2; weld marked SP; heat-affected zone marked SWC1, SWC2

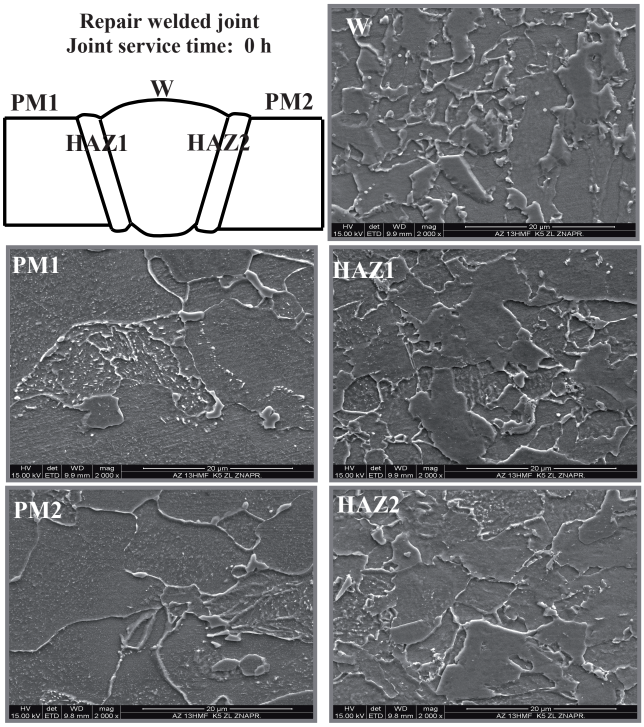

Fig. 4. Structure of the material of elements of tested repair welded joint, microstructure testing area: parent material marked MR1, MR2; weld marked SP; heat-affected zone marked SWC1, SWC2

The investigations of strength properties of the material of primary steam pipeline, welded joint after long-term service as well as new repair joint were carried out in the tensile test at room temperature and at temperature similar to the operating one (500°C) in order to determine the tensile strength (TS), yield point (YP), elongation (E) and reduction of area (P). The results of the investigations are presented in columns 5-8 of Table 3.

For the material of 13HMF steel pipeline after 218 000 h service, circumferential joint after service and repair circumferential joint the obtained tensile strength at room temperature and yield point at a temperature similar to the operating one was higher than the minimum values required for this steel in initial state pursuant to PN-75/H-84024, whereas for all the tested materials of the primary steam pipeline, joint after service and repair welded joint the obtained values of yield point at a temperature of 500°C, which is similar to the operating one, are lower than the minimum ones required for the tested steel in initial state [20]. For the elements from materials which do not meet these requirements the appropriately modified procedure for conducting water pressure tests should be developed and the need of possible modification to the procedure for starting up and shutting down the boiler should be considered. It will allow possible unexpected failures due to the lack of ability to transfer the required excessive loads to be avoided.

Table 2.
Review of the results of microstructural investigations of the material of jacket, circumferential welded joint of primary steam pipeline after 218 000 h service and repair circumferential welded joint

Testing area	Description of microstructure Material condition – exhaustion extent
Parent material of the primary steam pipeline	Ferritic-bainitic structure. Bainitic areas, mostly coagulated. At the ferrite grain boundaries, there are precipitates of diverse size, some of them rather significant. Inside the ferrite grains, there are very fine evenly distributed precipitates.
Parent material of the welded joint after service	No discontinuities and micro-cracks are observed in the structure. No initiation of damaging processes is observed.
Parent material of the repair welded joint	Bainitic areas: class I, precipitates: class a Damaging processes: class 0 **class 1/2, exhaustion extent: approx. 0.3**
Heat-affected zone, weld – joint after service - repair joint	Heat-affected zone structure. No discontinuities and micro-cracks are found in the structure.

Table 3.
Results of investigations of strength properties for tested elements of primary steam pipeline

Name of element	Specimen designation	Strength properties			
		TS	*YP*	*E*	YP^{500}
		MPa	**MPa**	**%**	**MPa**
Parent material of primary steam pipeline after service	**marked MR**	517	300	16	218
Joint after 218 000 h service	Weld **marked ZSf-SP**	513	336	15.5	277
Repair welded joint	Weld **marked ZSn-SP**	508	341	16.3	260
REQUIREMENTS FOR 13HMF STEEL IN INITIAL STATE TO PN-75/B-84024		**490-690**	**min 365**	**min 18**	**min 216**

1) designations according to standards applicable to initial state PN-75/H-84024

[shaded box] **— does not meet the requirements for material in initial state**

For tested materials the brittle fracture appearance transition temperature level was determined, and it differs according to the state of microstructure and corresponding exhaustion extent (Fig. 5). With increase in the exhaustion extent, the brittle fracture appearance transition temperature moves towards higher values [5]. As the brittle fracture appearance transition temperature of the parent material and circumferential welded joint after service is positive, the required boiler start-up and shutdown conditions should be followed absolutely [5].

To reduce the time of creep tests and evaluation of residual life, the abridged creep tests of a few dozen to max 10 thousand hours were used. This makes it possible to obtain test results within maximum several months, yielding good estimation of residual life, which has been verified by the own investigations of the Institute for Ferrous Metallurgy [2,10,16]. 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. The tests are conducted at constant test stress corresponding to the operating one and at different levels of test temperature, much higher than the operating one.

The abridged creep tests were carried out at constant test stress 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 results of abridged creep tests for the parent material, joint after service and repair joint of the primary steam pipeline carried out at constant 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 Figs. 6, 7 and 8.

The residual life determined for tested states of the material of primary steam pipeline based on abridged creep tests are summarised in column 2 of Table 4, whereas the disposable residual life of tested elements estimated on the same basis for the assumed parameters of further operation T_r = 540°C and σ_r = 55 MPa is summarised in column 3 of Table 4 and it represents the remained forecast time of further safe operation.

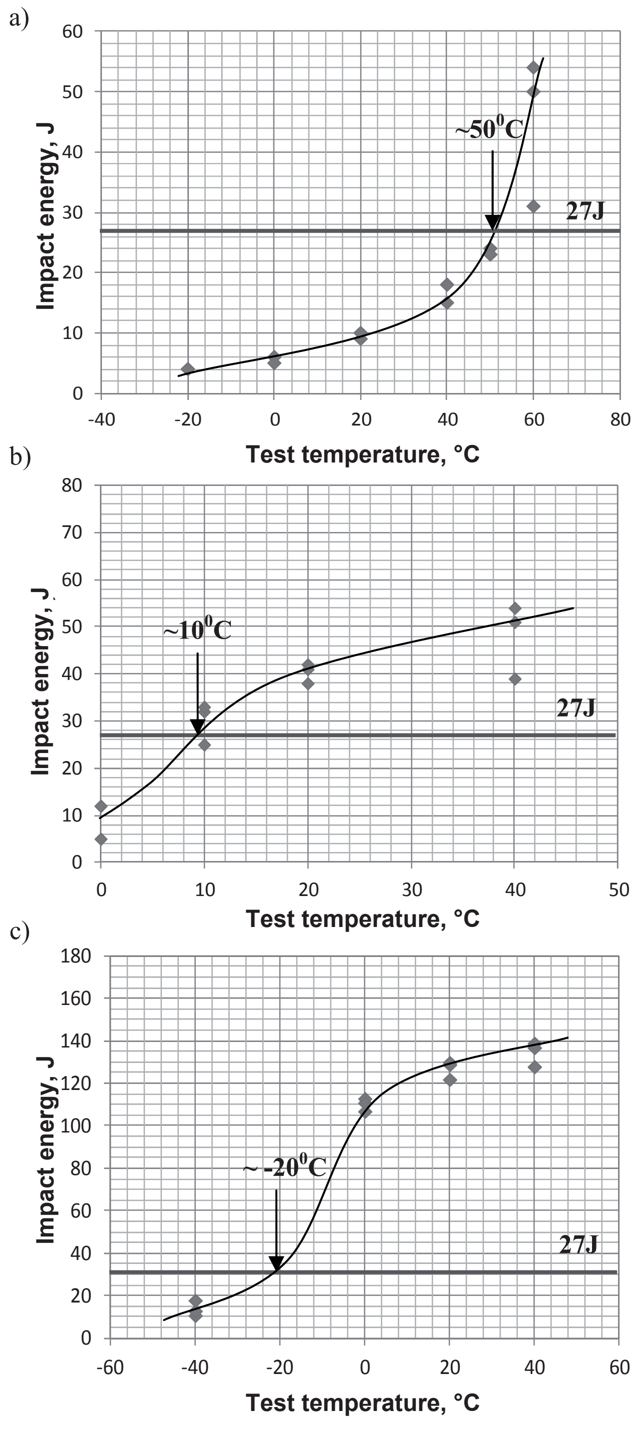

Fig. 5. Relationship between impact energy KV and test temperature T_b, and brittle fracture appearance transition temperature determined for tested: a) parent material of primary steam pipeline after service; b) circumferential welded joint after service; c) repair circumferential welded joint

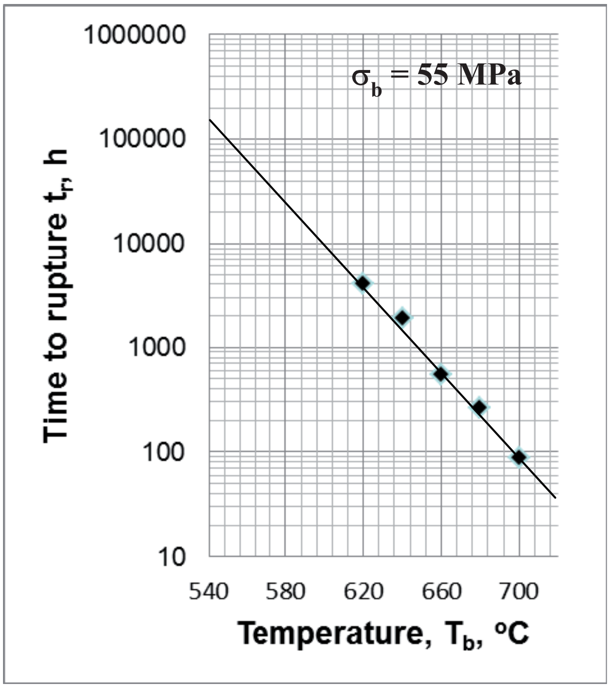

Fig. 6. Characteristics of creep-rupture strength for the parent material of primary steam pipeline after 218 000 h service

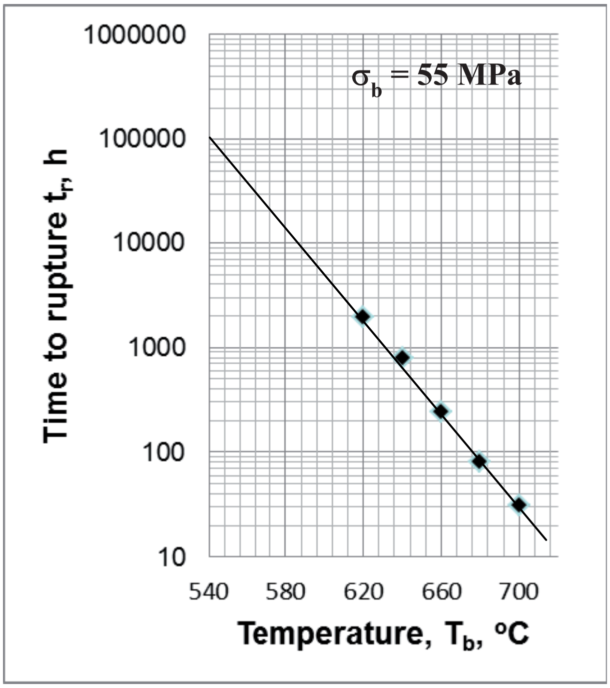

Fig. 7. Characteristics of creep-rupture strength for the material of primary steam pipeline welded joint of after 218 000 h service

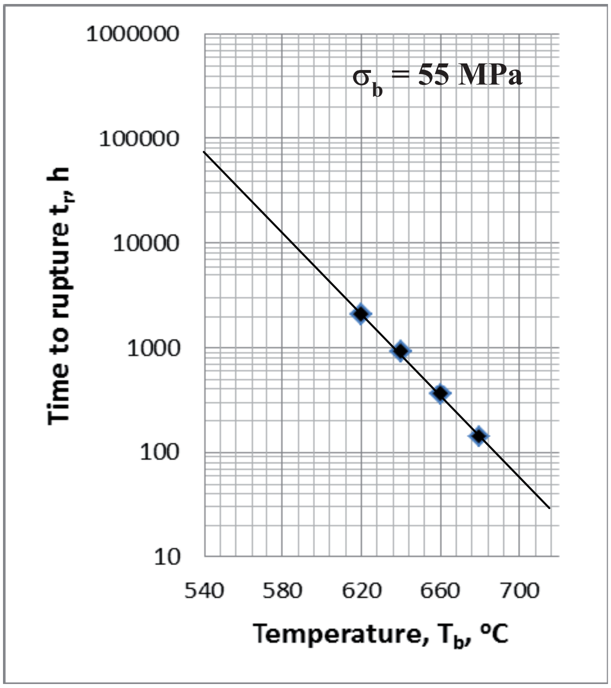

Fig. 8. Characteristics of creep-rupture strength for repair material of primary steam pipeline welded joint

Table 4.
Forecast residual life for the material 14MoV6-3 in initial state, material 14MoV6-3 after 218 000 h service and circumferential welded joint after 218 000 h service based on abridged creep tests

Designation	Residual life at 540°C	Disposable residual life at 540°C
1	2	3
After 218 000h h service – MR	220 000 h	120 000 h
After 218 000h h service – welded joint	120 000 h	66 000 h
Repair joint	100 000 h	55 000 h

5. Conclusions

1. For the material of both the primary steam pipeline and the circumferential welded joint after long-term service under creep conditions a similar exhaustion extent was

observed in structural investigations. For the circumferential welded joint after 218 000 h service rather slight changes in the image of structure were observed, which was confirmed by changes in hardness at cross-section of the joint from approx. 152 to 241 HV10.

2. For all the tested materials of the primary steam pipeline, joint after service and repair welded joint, the obtained values of yield point at a temperature of 500°C, which is similar to the operating one, are lower than the minimum ones required for the tested steel in initial state.
3. The impact strength of the parent material of primary steam pipeline after 218 000 h service measured at room temperature does not meet the requirements for the initial state in accordance with standards. It is also lower than the value assumed for the nil ductility transition temperature of 27 J. It requires close observance of the applicable boiler start-up and shutdown procedures. Also, for welded joint after 218 000 h service it is shifted towards positive temperature and equals to + 10°C. Nevertheless, further operation of the parent material and welded joint is possible. However, it requires close observance of the applicable boiler start-up and shutdown procedures.
4. The creep resistance tests of the 13HMF material, circumferential welded joint after 218 000 h service and repair welded joint revealed that the highest disposable residual life marked the parent material (120 000 h), whereas life time of the repair welded joint (55 000 h) was by 15% lower than the disposable residual life of the joint after service (66 000 h).
5. The procedure and type of investigations as presented herein are continued for different exhaustion extents of the material of 13HMF steel steam pipelines in order to determine the impact of the material condition on the life time of repair welded joints.

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