



The evaluation of suitability for operation of repair low-alloy steel welded joints

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ABSTRACT

Purpose: The purpose of the work was to evaluate the material condition of repair welded joints of steam pipelines with regard to their suitability for operation including determination of the time of their further safe operation.

Design/methodology/approach: The following was carried out: microstructure investigations using scanning electron microscopy, investigations on mechanical properties at room and elevated temperatures, determination of the fracture appearance transition temperature based on impact tests. The abridged creep tests without measurement of elongation during test were carried out to determine the material's residual life.

Findings: The time of safe operation was determined for welded joints made in 14MoV63 steel after long-term service and 14MoV63 steel after long-term service and in the as-received condition.

Practical implications: The applied methodology and the adopted procedures are used in evaluating the condition and forecasting further operation of new repair welded joints for the pressure part components of power equipment working under creep conditions.

Originality/value: The obtained results of investigations will be the elements of materials characteristics worked out by the Institute for Ferrous Metallurgy for the steels and welded joints made in them to work under creep conditions.

Keywords: Structure; Mechanical properties; Degradation after creep service; Residual life; Steel 14MoV63; Repair weld joint

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PROPERTIES

1. Introduction

Only few newly erected power units in the domestic power industry have been reported for the last several

years. Most of the currently operating power units have significantly exceeded the assumed design life time of 100,000 h, frequently exceeding 200,000 h of the actual service time. Therefore, keeping the electric energy

production level in Poland is mainly based on the operation of units working for a long time. However, it involves ensuring their availability and safe operation beyond the design service time taking into account the economic factor that forces the enhancement of their efficiency while respecting the environmental protection requirements in accordance with the applicable EC directive (Fig. 1) [1-7].

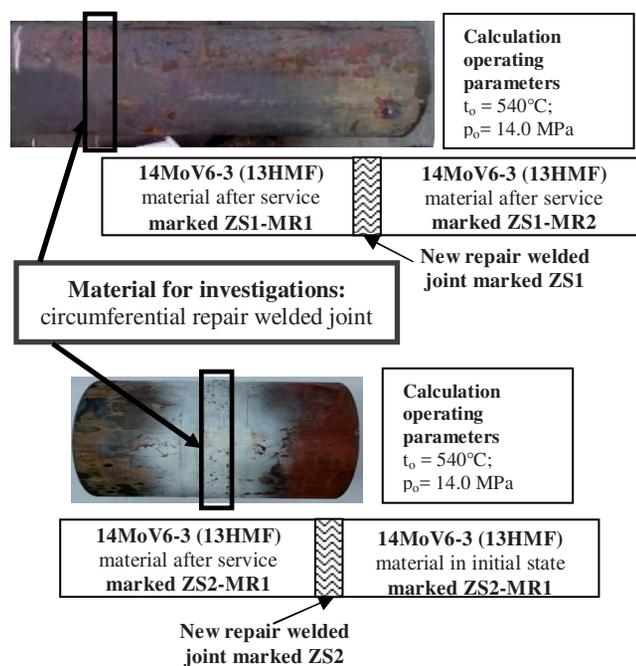


Fig. 1. Material for investigations in the form of new repair welded joints of: a) 14MoV6-3 steel primary steam pipeline (marked ZS1); b) 14MoV6 steel steam pipeline (marked ZS2)

Thus, extending the service time beyond the design one has become imperative, and making inspections and repairs with simultaneous reasonable diagnostics has acquired special significance [2]. These activities have a significant impact on the availability of the operating power units. As part of the diagnostics, not only the basic material of the operating components, but also the material of the welded joints is evaluated. The evaluation includes not only the welded joints after long-term service, but also the repair welded joints of materials after long-term service and materials after service, including, in particular, the repair welded joints of materials in the as-received condition and materials after long-term service [8-10].

The material condition evaluation of repair welded joints is necessary to determine the ability of a component to carry the required operating loads during its further operation. It will allow for a reliable estimation of the time of safe service of repair welded joints made during, but not limited to, the modernisation works on steam pipelines, in particular those operating beyond the significantly exceeded design service time. The subject of this study is the evaluation of material condition of new low-alloy steel repair welded joints and their suitability for further service. The applied research methods and the adopted procedure make it possible to correctly evaluate the condition of welded joints. In addition, the obtained results allowed the verification and extension of the database on materials for the energy industry after long-term service under creep conditions, including welded joints [11-14].

2. Material for investigations

The material for investigations was a specimen of the main 14MoV6-3 primary steam pipeline after long-term service under creep conditions and a specimen of the 14MoV6-3 steel primary steam pipeline in the as-received condition. The investigations were carried out on repair welded joints of the above-mentioned specimens. For the summary of the materials for investigations, see Figure 1.

The evaluation included the new repair welded joints of material after long-term service and material after service and the new repair welded joints of material in the as-received condition and material after long-term service.

2.1. Check analysis of chemical composition of the material of primary steam pipeline specimen

The chemical composition of the materials of the examined primary steam pipeline specimens with reference to the requirements of the standard specification is presented in Table 1. The results of the check analysis of chemical composition showed that both the material after long-term service and the material in the as-received condition the new repair welded joints marked ZS1 and ZS2 are made of meet the requirements of the standard with regard to chemical composition of the examined 14MoV6-3 steel.

Table 1.
Chemical composition of the material of examined 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	0.10	0.40	0.15	max 0.04	max 0.04	max 0.25	0.30	max 0.30	0.50	V 0.22-0.35
14MoV6-3	0.18	0.70	0.35				0.60		0.65	Al max 0.02
14MoV6-3 (13HMF) after service marked ZS1-MR1	0.10	0.50	0.25	0.012	0.014	0.10	0.36	0.053	0.51	V 0.23
14MoV6-3 (13HMF) after service marked ZS1-MR2	0.11	0.46	0.26	0.020	0.021	0.034	0.38	0.051	0.58	V 0.32
14MoV6-3 (13HMF) after service marked ZS2-MR1	0.11	0.51	0.22	0.010	0.020	0.11	0.45	0.075	0.53	V 0.29 Al 0.02
14MoV6-3 (13HMF) in the as-received condition marked ZS2-MR1	0.12	0.61	0.20	0.015	0.007	0.15	0.54	0.092	0.52	V 0.25 Al 0.01

3. Scope of investigations

Non-destructive materials testing was carried out at designated points on the new repair welded joints from the primary steam pipeline specimens acquired for investigations including:

- microstructure investigations using scanning electron microscopy (SEM),
- investigations on mechanical properties at room and elevated temperatures,
- static tensile test,
- determination of brittle fracture appearance transition temperature based on impact tests,
- hardness tests on metallographic microsections,
- abridged creep tests without measurement of elongation during test in order to determine the material's residual life.

Based on the results of the above-mentioned investigations, the material condition of the examined new repair welded joints and their suitability for further service was evaluated and the time of their safe service was determined.

4. Results of investigations

4.1. Microstructure investigations

The microstructure investigations on microsections were carried out after grinding, polishing and etching.

The observations were made under the scanning electron microscope Inspect F with magnifications of 500, 1000, 2000 and 5000x. The results of examinations as selected microstructure images are shown in Fig. 2a for the elements of the new repair joint marked ZS1 and in Fig. 2b for the elements of the new repair joint marked ZS2. The description of microstructure including the evaluation and exhaustion extent t_c/t_r estimated based on own classification of the Institute for Ferrous Metallurgy is provided in Table 2.

4.2. Mechanical testing

The investigations on strength properties were carried out as part of tensile test at room temperature and at an elevated temperature similar to the actual operating one (500°C). The obtained results of the tensile strength (R_m) and yield point (R_e , R_{e1}) tests are shown in Fig. 3, while the results of impact energy tests, carried out on longitudinal V-notched test pieces cut perpendicularly to the surface of the examined pipes, are shown in Fig. 4. The impact energy tests were carried out at the temperature values selected so that it was possible to determine brittle fracture appearance transition temperature for the material of the examined elements.

Hardness of the new repair circumferential welded joints on transverse metallographic microsection was measured with a hardness tester by Vickers HV10 method.

Hardness measurement results for the new repair welded joint marked ZS1 are shown in Fig. 5a and for the joint marked ZS2 in Fig. 5b, respectively. Hardness test

results are also summarised in Table 2 in relation to structure condition of the material of new repair welded joints of the primary steam pipeline.

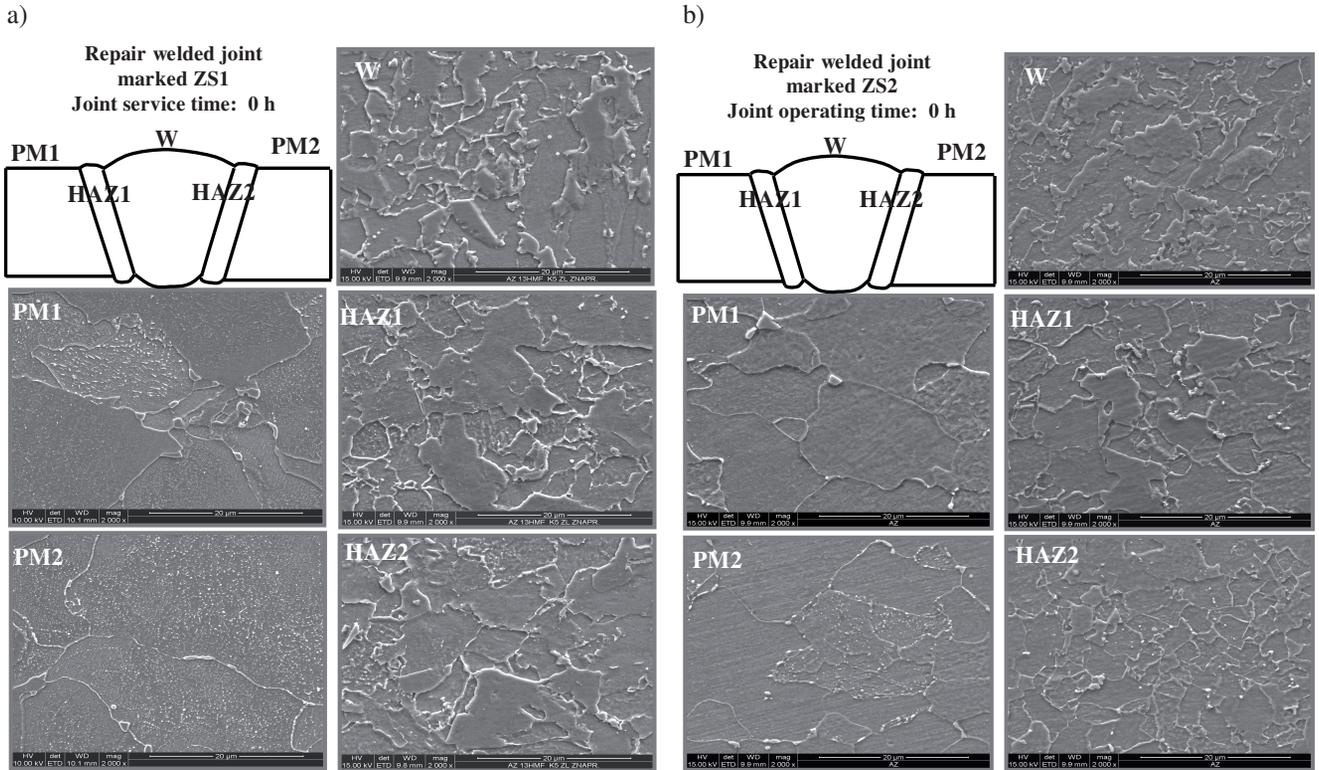


Fig. 2. Microstructure of the material of elements of the examined new repair welded joints. Area of microstructure investigations: parent material marked MR1, MR2; weld metal marked SP; heat-affected zone marked HAZ1, HAZ2

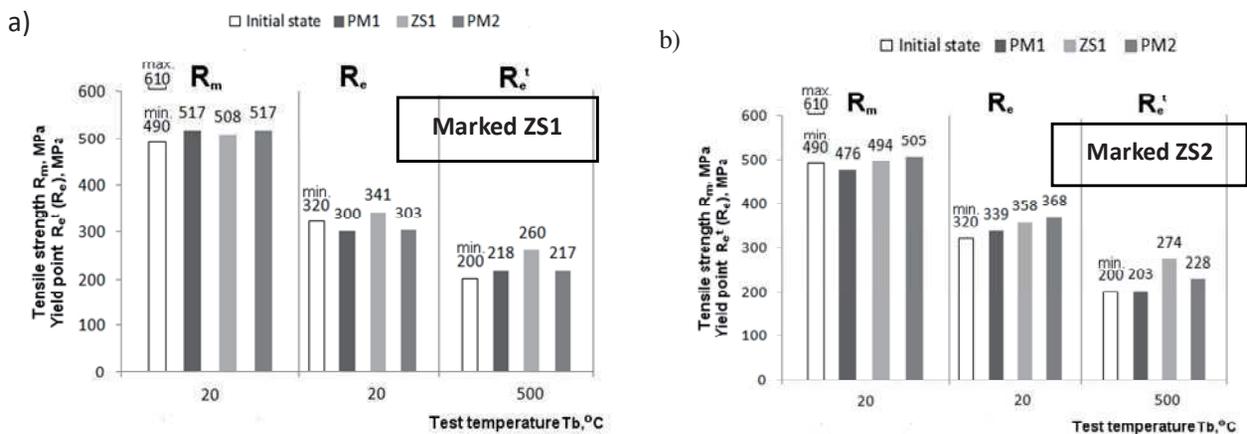


Fig. 3. Results of investigations on mechanical properties of the materials of examined elements of new repair welded joints in the primary steam pipeline specimens, in particular: tensile strength and yield point at room and elevated temperature

Table 2.

Evaluation of the results of microstructure investigations on the material of new repair welded joints of the primary steam pipeline

Material for investigations	Description of microstructure Material condition – exhaustion degree	Hardness HV10
New repair welded joint of the primary steam pipeline Grade: 14MoV6-3 (13HMF) Service time: 0h marked ZS1	PM1/PM2 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 <u>Damaging processes: class O</u> CLASS 1/2, EXHAUSTION DEGREE: approx. 0.3	157
	HAZ1/HAZ2 Heat-affected zone structure. No discontinuities and micro-cracks are observed in the structure.	297/ 309
	W Structure of weld material in welded joint. No discontinuities and micro-cracks are observed in the structure.	250
	PM1 Ferritic-bainitic structure. Partially coagulated bainitic areas. Numerous precipitates of various sizes at the ferrite grain boundaries. Numerous fine or small precipitates inside the ferrite grains, distributed rather evenly. No discontinuities and micro-cracks are observed in the structure. No initiation of damaging processes is observed. Bainitic areas: class I, precipitates: class a/b <u>Damaging processes: class O</u> CLASS 2, EXHAUSTION DEGREE: approx. 0.3-0.4	146
New repair welded joint of the primary steam pipeline Grade: 14MoV6-3 (13HMF) Service time: 0h marked ZS2	PM2 Ferritic-bainitic structure. Microstructure characteristic of the examined steel in the as-received condition. No discontinuities and micro-cracks are observed in the structure. Bainitic areas: class 0, precipitates: class o; <u>Damaging processes: class O</u> CLASS 0, EXHAUSTION DEGREE: 0	155
	HAZ1/HAZ2 Heat-affected zone structure. No discontinuities and micro-cracks are observed in the structure.	262/ 279
	W Structure of weld material in welded joint. No discontinuities and micro-cracks are observed in the structure.	229

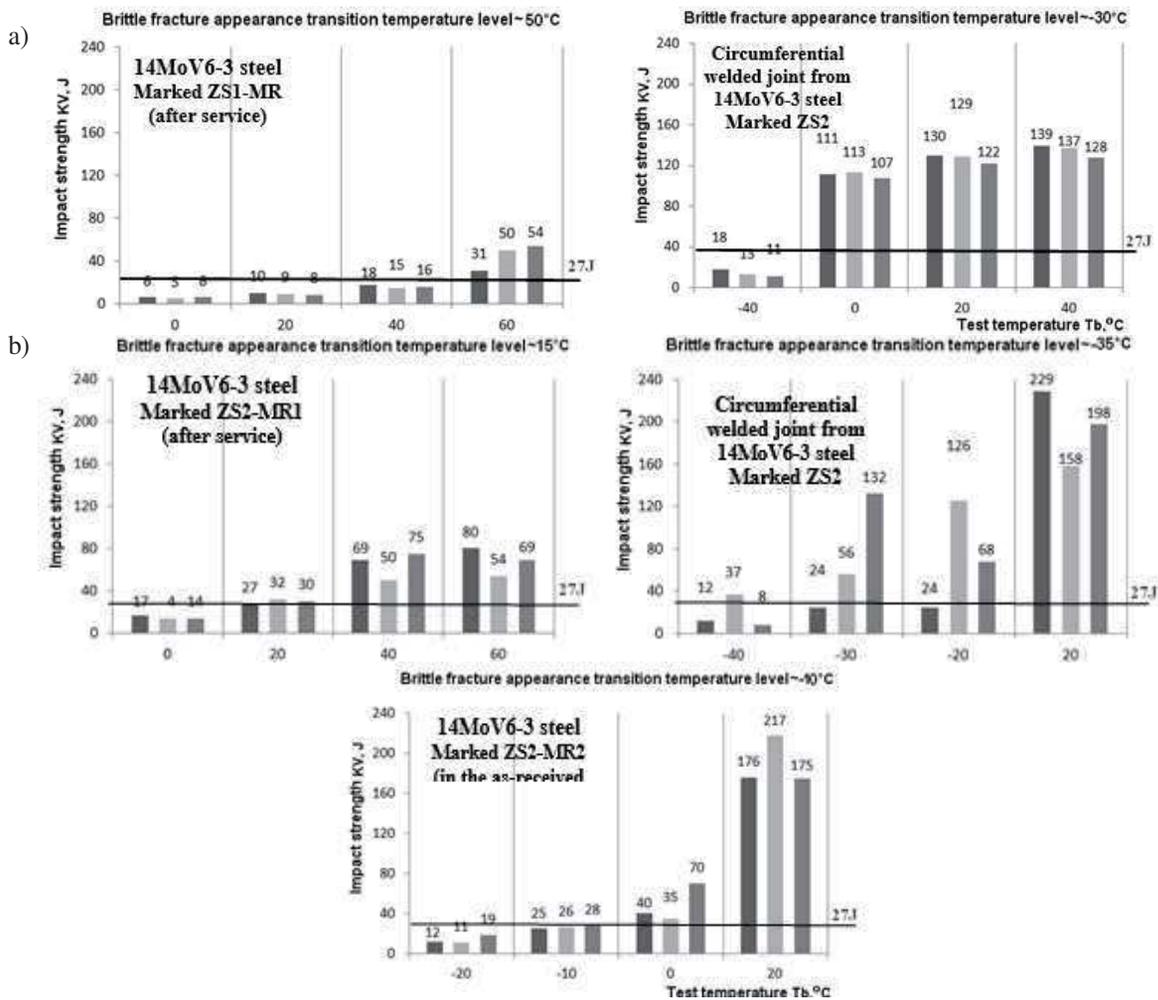


Fig. 4. Results of investigations on mechanical properties of the materials of examined elements of new repair welded joints in the primary steam pipeline specimens, in particular impact energy at various test temperature levels, for: a) new repair welded joint marked ZS1; b) new repair welded joint marked ZS2 in the primary steam pipeline specimens

Abridged creep tests

In order to reduce the time of performed creep tests and evaluate the residual life, the abridged creep tests with duration of a few dozen to max 3 to 5 thousand h were used. This provides an opportunity of obtaining test results within maximum several months, with good estimation of residual life. The creep process acceleration and reduction in testing time are obtained in creep tests performed at a uniaxial tension on test pieces taken from the examined material by conducting the tests [1,2]:

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

The broad convergence between the results obtained in abridged creep tests conducted at a constant stress corresponding to the operating one and those obtained in long-term creep tests conducted as part of own investigations carried out at the Institute for Ferrous Metallurgy positively verified this method and allowed its application in the engineering practice.

Therefore, for the examined new repair welded joints, the abridged creep tests were carried out. The tests were carried out at a constant test stress level corresponding to the operating one $\sigma_b = \sigma_r = \text{const}$ and at a constant test temperature T_b for each of the tests, but with different values ranging between 620°C and 700°C in 20°C intervals. The results of the tests are presented as the relationship $\log t_r = f(T_b)$ at $\sigma_b = \text{const}$, where t_r is time to rupture in the creep test. They allow plotting the straight line inclined to

the time to rupture t_r axis. The residual life is determined by extrapolation of the obtained straight line towards the lower temperature corresponding to the operating one T_c .

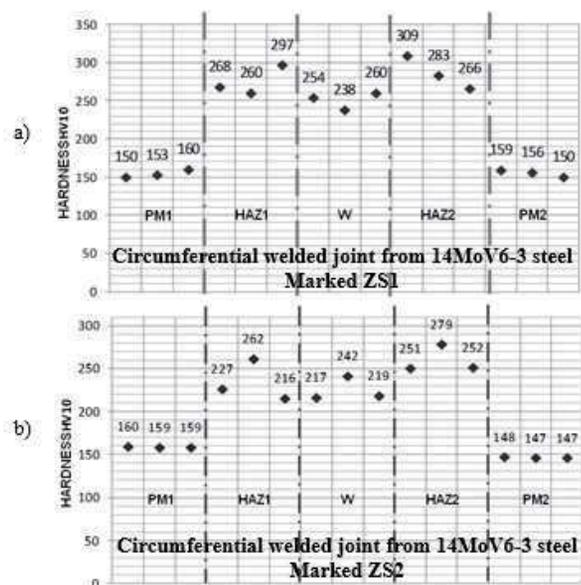


Fig. 5. Results of hardness measurement for: a) new repair welded joint from 14MoV6 steel after service marked ZS1; b) new repair welded joint from 14MoV6 steel after service and in the as-received condition marked ZS2

The obtained results of abridged creep tests for the new repair circumferential welded joint of material after long-term service and material after service, marked ZS1, carried out at a constant stress $\sigma_b = 55$ MPa, corresponding to the assumed working stress σ_r of further service, are shown as the relationship $\log t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ in Fig. 6 and summarised in Table 3.

In contrast, the obtained results of the abridged creep tests for the new repair circumferential welded joint of material after long-term service and material after service, marked ZS2, carried out at a constant stress $\sigma_b = 55$ MPa, corresponding to the assumed working stress σ_r of further service, are shown as the relationship $\log t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ are shown in Fig. 6 and summarised in Table 3.

Table 3.

Results of abridged creep tests at a constant test stress level and for different levels of temperature higher than the expected operating one for the material of new repair welded joints of a primary steam pipeline from 14MoV6-3 steel

Designation	Test stress σ_b , MPa	Test temperature, T_b , °C				
		620	640	660	680	700
New repair welded joint marked ZS1	55	2134	914	363	143	56
New repair welded joint marked ZS2		1743	724	265	123	46

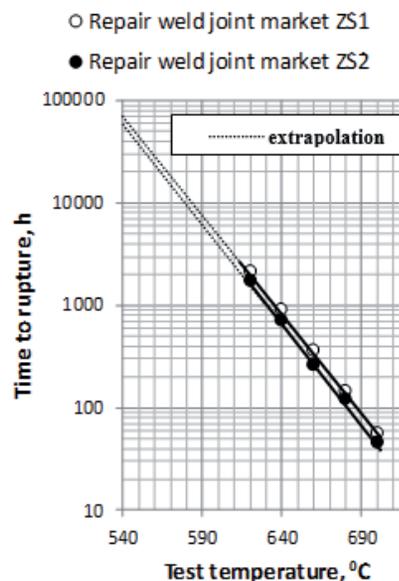


Fig. 6. Results of abridged creep tests of the repair circumferential welded joints marked ZS1; ZS2 as the relationship $\log t_{re} = f(T_b)$ at $\sigma_b = 55$ MPa

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

The assessment of material condition and determination of residual life – discussion of the results

The applied range of investigations and research methods enable the assessment of material condition, its ability to carry the required operational loads and determination of the time of further safe service. The assessment is based on total evaluation of the results of investigations on microstructure, basic mechanical properties and creep tests of the examined new repair circumferential welded joints made from 14MoV6-3 steel, marked ZS1 and ZS2.

Table 4.

Residual life and disposable residual life based on abridged creep tests of the materials of examined new circumferential welded joints

Designation ^{1.)}	Adopted operating stress σ_r , MPa	Adopted further operation temperature T_r , °C	Determined life, h ^{2.)}	
			residual	disposable residual
New repair welded joint ZS1	55	540	80.000	48.000
New repair welded joint ZS2		540	60.000	36.000

Note: ^{1.)} Designations according to standards applicable to the as-received condition as per PN-75/H-84024,

^{2.)} provided that the amount of plastic strain after long-term service so far does not exceed max 1%.

Since the degree of microstructure degradation is the reason for the loss of required performance, the assessment of microstructure, based on own classification of the Institute for Ferrous Metallurgy related to the exhaustion degree, is performed in the first place.

The structure of the examined materials consists of ferrite with bainite. The examined selected materials differ in the form of bainite and the state of development of carbide precipitation processes. In accordance with the Institute for Ferrous Metallurgy's own classification, the ZS1 joint material is characterised by material condition corresponding to class 1/2 with exhaustion degree of approx. 0.3 (Table 2). The condition of the ZS2 joint material after service corresponds to class 2 with exhaustion degree of 0.3-0.4 (Table 2), while the ZS2 joint material in the as-received condition characterised by class 0 with exhaustion degree of 0. Moreover, the structure of the welds and heat affected zones showed no initiation of the internal damaging processes (damage class 0).

Also, hardness of the examined elements of new repair welded joints is much lower than the maximum permissible one equal to 350 HV. In both cases, mild changes in hardness during the transition from the parent material through the heat affected zone to the weld metal were revealed (Fig. 5, Table 2).

Regardless of the structure class of the parent material as well as the heat affected zone and weld metal for the repair welded joint marked ZS1 at room temperature, the tensile strength level is higher and the yield point level is lower for the parent material and higher for the welded joint than the required minimum values for the base material in the as-received condition (Fig. 3).

For the repair welded joint marked ZS2, the requirement for tensile strength and yield point at room temperature is satisfied, with the exception of the parent material after service for which the tensile strength is lower than the minimum required value for the base material (Fig. 3).

The obtained results for yield point at 500°C of both the examined new repair welded joints are higher than the minimum required values for the base material in case of both the parent material and the welded joint (Fig. 3).

The impact energy of the weld material and the parent material in the as-received condition, measured on V-notched impact-test specimens at room temperature, significantly exceeds the minimum expected value of 27 J. Also, the brittle fracture appearance transition temperature of the weld material runs at a level of approx. -30°C and -35°C for the joints marked ZS1 and ZS2, respectively (Fig. 4). The results of investigations on these features that characterise the formability should be considered satisfactory. However, it should be noted that with the increase in exhaustion degree the brittle fracture appearance transition temperature offset to a higher value is observed.

Based on the results of investigations obtained so far, just some examples of which can be found in this study, it can be concluded that the highest dynamics in offsetting of this temperature to its higher level, out of the most often used steel grades being analysed, occurs in 14MoV6-3 steel [1].

As the brittle fracture appearance transition temperature of the parent material after service for both the repair welded joints is positive, it is essential to observe the required conditions for starting up and shutting down the boiler.

The residual life determined by extrapolation of creep results obtained in the abridged tests, for the temperature of further service and the adopted stress level of further operation of the base materials and repair welded joints, allowed the disposable residual life, being the time of further safe service, to be determined.

The residual life t_{re} determined for the repair welded joint of the materials after service, marked ZS1, is 80 thousand hours and the determined disposable life t_b is 48 thousand hours (Fig. 6, Table 4), while the residual life t_{re} determined for the repair welded joint of the material after service and the material in the as-received condition, marked ZS2, is 60 thousand hours and the determined disposable life is 36 thousand hours (Fig. 6, Table 4).

The time of safe service of the examined new repair welded joints can be assumed to be 48 thousand hours for the ZS1 joint and 36 thousand hours for the ZS2 joint.

5. Summary

In conclusion, it can be stated that the examined repair welded joints are suitable for operation for a limited time, which results from the disposable residual life determined for defined temperature and stress parameters of further service. In all operations related to starting up and shutting down the plant, water tightness tests as well as repair and upgrade operations, the actual microstructure condition and obtained properties have to be taken into account.

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

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References

- [1] A. Hernas, J. Dobrzański, *Life-time and Damage of Boilers and Steam Turbines Elements*, Publishing House of the Silesian University of Technology, Gliwice, 2003 (in Polish).
- [2] J. Dobrzański, *Materials science interpretation of the life of steels for power plants*, Open Access Library 3, 2011 (in Polish).
- [3] J. Okrajni, A. Marek, G. Junak, Description of the deformation process under thermo-mechanical fatigue, *Journal of Achievements in Materials and Manufacturing Engineering* 21/2 (2007) 15-24.
- [4] 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.
- [5] M. Dziuba-Kałuża, J. Dobrzański, A. Zieliński, Mechanical properties of Cr-Mo and Cr-Mo-V low-alloy steel welded joints after long-term service under creep conditions, *Archives of Materials Science and Engineering* 63/1 (2013) 5-12.
- [6] J. Dobrzański, A. Zieliński, The assessment of suitability for further operation of the material of 14MoV63 (13HMF) steel primary steam pipeline elements after 200 000 h service under creep conditions, *Thematic Booklet* 18 (2008) 32-36.
- [7] A. Zieliński, J. Dobrzański, M. Dziuba-Kałuża, Structure of welded joints of 14MoV6-3 and 13CrMo4-5 steel elements after design work time under creep conditions, *Archives of Materials Science and Engineering* 61/2 (2013) 69-76.
- [8] M. Dziuba-Kałuża, J. Dobrzański, A. Zieliński, Life time of circumferential welded joints of critical elements of Cr-Mo and Cr-Mo-V low-alloy steel boilers after long-term service beyond the design time, *Transactions of the Institute for Ferrous Metallurgy* 65/3 (2013) 64-66.
- [9] M. Dziuba-Kałuża, J. Dobrzański, The evaluation of suitability for operation of welded joints of critical elements in the pressure part of power units from Cr-Mo and Cr-Mo-V low-alloy steels after service beyond the design work time based on the investigation of mechanical properties and microstructure, *Monograph: Materials and technologies used for construction of boilers with supercritical parameters at up to 700°C*, 2013.
- [10] M. Sroka, A. Zieliński, Matrix replica method and artificial neural networks as a component of condition assessment of materials for the power industry, *Archives of Materials Science and Engineering* 58/2 (2012) 130-136.
- [11] A. Zieliński, J. Dobrzański, M. Sroka, Changes in the structure of VM12 steel after being exposed to creep conditions, *Archives of Materials Science and Engineering* 49/2 (2011) 103-111.
- [12] J. Dobrzański, M. Sroka, Computer aided classification of internal damages the chromium-molybdenum steels after creep service, *Journal of Achievements in Materials and Manufacturing Engineering* 24/2 (2007) 143-146.
- [13] A. Zieliński, J. Dobrzański, G. Golański, M. Sroka, Computer-assisted analysis of changes in the microstructure of P92 steel after exposure at elevated temperature, *Archives of Materials Science and Engineering* 65/2 (2014) 77-86.
- [14] A. Zieliński, G. Golański, M. Sroka, J. Dobrzański, Estimation of long-term creep strength in austenitic power plant steels, *Materials Science and Technology* 32/8 (2016) 780-785.