metals

Article

Assessment of the Residual Life of Steam Pipeline Material beyond the Computational Working Time

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Academic Editor: Robert Tuttle
Received: 19 December 2016; Accepted: 28 February 2017; Published: 6 March 2017

Abstract: This paper presents the evaluation of durability for the material of repair welded joints made from (13HMF) 14MoV6-3 steel after long-term service, and from material in the as-received condition and after long-term service. Microstructure examinations using a scanning electron microscope, hardness measurements and creep tests of the basic material and welded joints of these steels were carried out. These tests enabled the time of further safe service of the examined repair welded joints to be determined in relation to the residual life of the materials. The evaluation of residual life and disposable life, and thus the estimation and determination of the time of safe service, is of great importance for the operation of components beyond the design service life. The obtained test results are part of the materials' characteristics developed by the Institute for Ferrous Metallurgy for steels and welded joints made from these steels to work under creep conditions.

Keywords: creep; degradation; welded joint; Cr-Mo-V steel; residual life

1. Introduction

Pressure components working at an elevated temperature are designed for a definitive working time. This time is based on temporary creep strength used for calculations. It is 100,000 h for old units, while, for those with supercritical working parameters designed and operated at present, it is 200,000 h. Most of the units operated in Poland have significantly exceeded the design service life of 100,000 h, reaching the actual operation time of more than 200,000 h. The extension of the operation time beyond the design one of 100,000 h is made by using the calculation methods based on data concerning the average temporary creep strength for 200,000 h and positive results of comprehensive investigations and diagnostic measurements. Usually, the critical components in the pressure part of boilers and turbines are subject to these investigations and evaluation. Out of these components, those working above the limit temperature, i.e., under creep conditions, are crucial (Figure 1).

The above-mentioned operation of steam boilers for much more than 200,000 h requires a new approach in the materials diagnostics. For safety reasons, a particularly important issue to be solved is creep strength of the welded joints of the steam pipelines working under creep conditions [1–6].

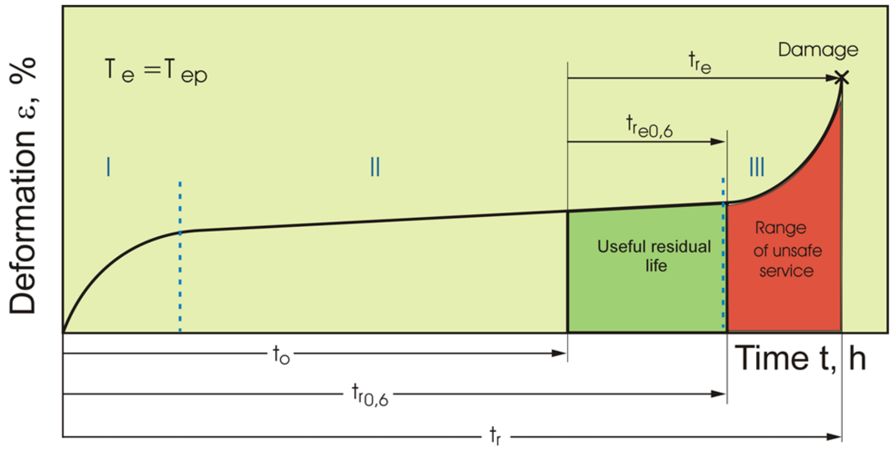


Figure 1. Schematic approach of the definition of residual and disposable durability.

In the evaluation of these components, it is important and necessary to evaluate the condition of their material [7–13]. This evaluation is carried out based on non-destructive or destructive materials tests. In the case of components working for more than 150,000 h, the estimate of residual life by non-destructive testing is not sufficient. It needs to be determined based on destructive tests performed on a sampled representative test specimen [14].

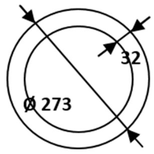
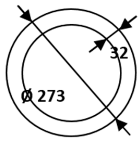
As part of the diagnostics, not only the basic material of the operated component but also the material of welded joints is subject to evaluation [15]. It is necessary to evaluate the condition of the material of welded joints to determine the component's ability to carry the required operating loads during its further service. If there is a need for repair to or replacement of a part or the entire component with a new one, the ability of the basic material under operation to carry out such a repair or replacement must be determined. When the condition of such material after service allows a repair to be made, it is necessary to develop a technology for its performance. The repair welded joint is defined as a new weld made to join a material after service with another material after service, and also to join a new material with a material after service (for replacement of a part of a structural component with a new one). Such repair welded joints are made during the renovation and modernisation works on pressure elements including, but not limited to, steam pipelines.

The subject-matter of the investigations, including the materials and their repair welded joints after long-term service made with materials after service or new materials, is an important issue overseen by the Institute for Ferrous Metallurgy. The selected results of investigations with regard to condition evaluation of the material of repair welded joints are the subject of this study. They mainly concern the elements of primary steam pipelines made from 13HMF (14MoV6-3) steel, which in the majority of Polish power plants exceeded the design service life of 100,000 h. Therefore, an important issue in the evaluation of the safe operation of these devices is to provide a numerical value of the time of their further operation and determine creep strength not for the material pipeline itself, but rather for the welded joints of these materials made during repairs.

2. Material for Investigations

The material for investigations was tested specimens of repair welded joints made from (13HMF) 14MoV6-3 steel after long-term service, and of material in the as-received condition and after long-term service. The summary of the material for investigations, including their steel grades, geometrical dimensions, working parameters, the current time of service and macrophotography of the test specimen is presented in Table 1.

Table 1. Material for investigations.

Repair Welded Joint Made from Pipeline Sections after Long-Term Service, Marked ZS1		
Steel grade: 14MoV6-3 Service time: material after 169,000 h service, marked ZS1		
Dimensions: 273 × 32 ($D_n \times g_n$)		
Working parameters of sections after service t_0 = 538 °C; p_0 = 13.0 Mpa		
Material for investigations: repair circumferential welded joint made under industrial conditions		
Repair Welded Joint Made from Pipeline Sections in the As-Received Condition (before Service) and after Long-Term Service, Marked ZS2		
Steel grade: 14MoV6-3 Service time: material in the as-received condition/material after 169,000 h service, marked ZS2		
Dimensions: 273 × 32 ($D_n \times g_n$)		
Working parameters of sections after service t_0 = 538 °C; p_0 = 13.0 Mpa	 	
Material for investigations: repair circumferential welded joint made under industrial conditions		

The check analysis of chemical composition of the examined materials of repair welded joints from low-alloy Cr-Mo-V steels after long-term service and a material in the as-received condition and after long-term service was performed in accordance with the following procedures: 3/CHEM,4 "Determination of C, Mn, Si, P, S, Cr, Ni, Cu, Mo, V, Ti, Al, Nb, B and Sn contents in low- and medium-alloy carbon steel by the spark optical emission spectrometry method using natural standards" with the optical emission spectrometer Magellan Q8 by Bruker, Germany. For the chemical composition of the examined steels with regard to the requirements of standard specification [16], see Table 2.

Table 2. Check analysis of chemical composition.

Grade of Material	Content of Elements (%)									
	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Others
14MoV6-3 according to [16]	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
14MoV6-3 169,000 h service Designation ZS1-PM1	0.16	0.58	0.35	0.017	0.018	0.20	0.46	0.23	0.62	V 0.29 Al 0.026
14MoV6-3 169,000 h service Designation ZS1-PM2	0.16	0.58	0.35	0.017	0.020	0.20	0.46	0.23	0.63	V 0.29 Al 0.024
14MoV6-3 in the as-received condition Designation ZS2-PM1	0.17	0.51	0.22	0.008	0.006	0.11	0.53	0.11	0.52	V 0.26 Al 0.013
14MoV6-3 169,000 h service Designation ZS2-PM2	0.16	0.59	0.34	0.018	0.018	0.21	0.48	0.22	0.59	V 0.28 Al 0.023

The analysis results of the check of chemical composition show that the materials of the examined test specimens of repair welded joints meet the requirements of the standard with regard to the chemical composition of the examined steel grade, i.e., 13HMF (14MoV6-3) [16].

3. Research Scope and Methodology

As part of the investigations, the properties of the material of the repair welded joints were evaluated. In the evaluation of the material condition and the level of required utility properties for repair welded joints, the following was subject to investigation:

- The microstructure of repair circumferential welded joints of components in the pressure part of a boiler was examined, with tests were carried out using a scanning electron microscope (SEM, FEI, Hillsboro, OR, USA) Inspect F on nital-etched metallographic microsections;
- Analysis of precipitation processes was carried out using X-ray analysis of isolated carbides, with the use of a Empyrean diffractometer (XRD, Panalytical, Almelo, Netherlands) and selective diffraction of electrons;
- The level of hardness for individual joint components and its nature in the course from the parent material through the heat-affected zone and weld was obtained, taken by Vickers method using a Future—Tech FM—7 machine (Kawasaki, Japan) at the indenter load of 10 kG;
- The material's residual life was determined based on abridged creep tests at a constant test stress corresponding to the operating one $\sigma_b = \sigma_r$ = const and at a constant test temperature T_b for each test. The tests were performed using Instron single-sample machines (Norwood, MA, USA) with an accuracy of temperature during the test of ±1 °C.

The obtained results of the investigations are part of the study, which is under preparation for verification of the proposed method for evaluating and predicting the time of further safe service of homogeneous circumferential welded joints from low-alloy Cr-Mo-V steels. In the case of its positive result, this test method will be used in materials diagnostics to be performed for the power industry.

4. Results

4.1. Microstructure Investigations: Structure of Steel in the As-Received Condition

The microstructure of 14MoV6-3 steel in the as-received condition is a mixture of bainite and ferrite, sometimes with a slight amount of pearlite. Moreover, very fine MC carbide precipitates that occur inside the ferrite grains are observed within the structure. In the bainite areas, there are small spheroidal cementite precipitates, while in the pearlite colonies, cementite lamellas exist. An example of the characteristic microstructure of 14MoV6-3 steel in the as-received condition is shown in Figure 2.

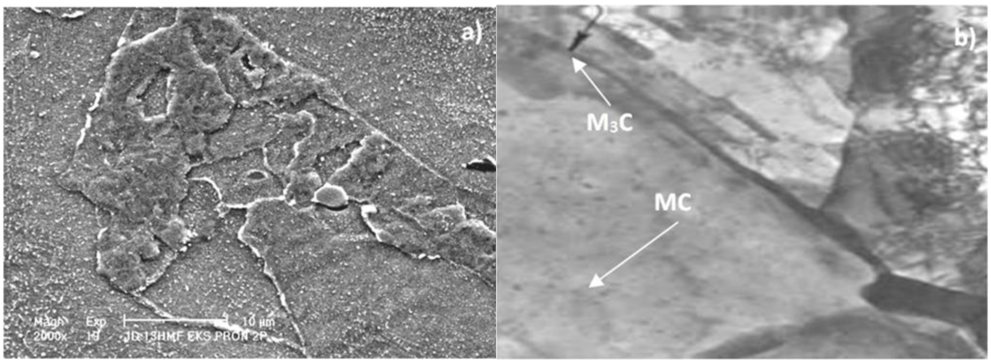


Figure 2. Structure image of 14MoV6-3 ferritic-bainitic steel in the as-received condition (**a**) SEM; (**b**) TEM.

4.2. Evaluation of the Microstructure of Repair Welded Joints

The investigations of microstructure were carried out on metallographic microsections. The microsections were made on the cross-section of test specimens of the examined components in the area of the weld and prepared by mechanical grinding and polishing as well as etching. The observations were performed with magnifications of 500 to 5000×. For the repair welded joint made from materials after long-term service, marked ZS1, the results of the investigations are presented as photographs of the microstructure of the materials of the circumferential welded joint components, in particular: parent material, heat affected zone of the joint and weld, respectively, in Figure 3.

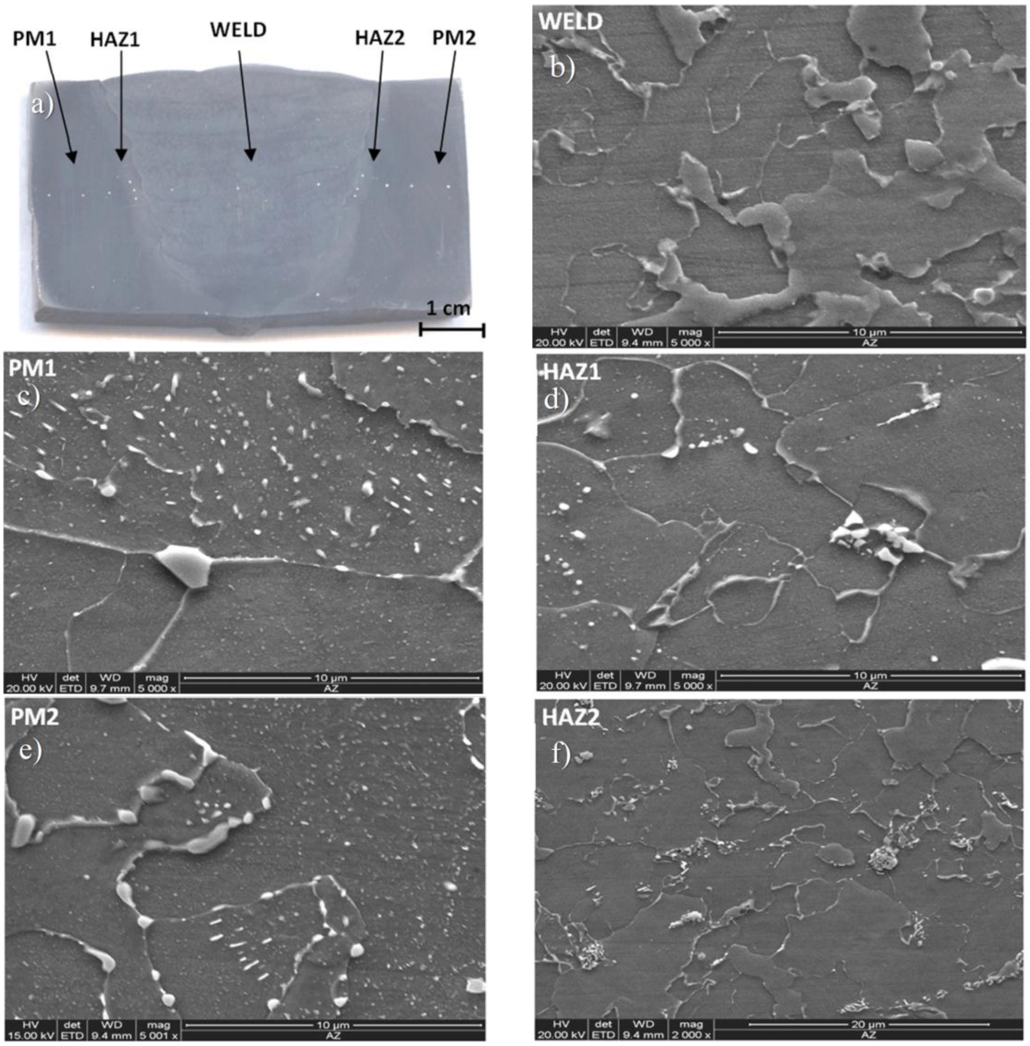


Figure 3. Structure of the material of components of the repair welded joint marked ZS1 made from 14MoV6-3 steel after 169,000 h service; microstructure investigation locations (**a**): parent material marked (**c**) PM1, (**e**) PM2; heat affected zone marked (**d**) HAZ1, (**f**) HAZ2; weld marked (**b**) WELD.

The results of the microstructure investigations for the components of the repair welded joint made from a material in the as-received condition and after long-term service, marked ZS2, in particular: parent material, heat affected zone and weld, are provided in Figure 4.

The classification of the microstructure including the evaluation and exhaustion extent t_e/t_r estimated based on the Institute for Ferrous Metallurgy's own classification [1] is provided in Table 3.

The parent material of the welded joints marked ZS1 (PM1, PM2) and ZS2 (PM2) after service was characterised by a ferritic microstructure with partially coagulated bainite areas. At the ferrite grain boundaries, there are precipitates of different size, mostly fine ones, whereas inside the ferrite grains, mostly very fine precipitates distributed evenly within the structure were observed.

The microstructure of the parent material of the welded joint marked ZS2 (PM1) in the as-received condition was characterised by ferritic-bainitic microstructure, which is typical for this type of steel.

In the microstructure of the materials of the examined repair welded joints, no discontinuities or microcracks, nor initiation of internal damage processes due to creep, were observed.

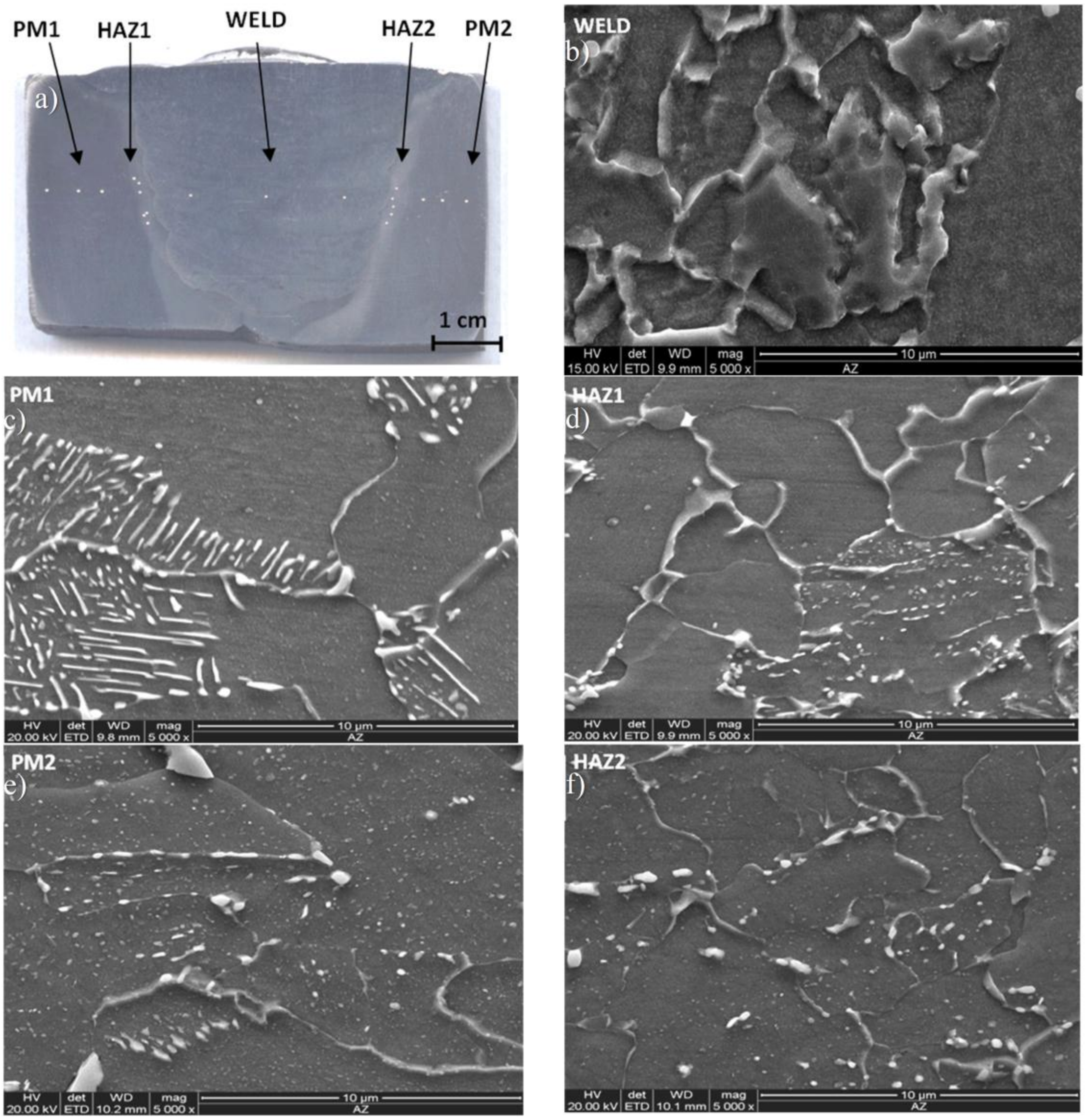


Figure 4. Structure of the material of components of the repair welded joint marked ZS2 made from 14MoV6-3 steel in the as-received condition and after 169,000 h service; investigation performance locations (**a**): parent material marked (**c**) PM1, (**e**) PM2; heat affected zone marked (**d**) HAZ1, (**f**) HAZ2; weld marked (**b**) WELD.

Table 3. Review of the results of microstructure investigations and hardness tests on the material of components of repair welded joints.

Material for Investigations		Figure No.	Description of Microstructure Material Condition—Exhaustion Degree	Hardness HV10
Repair welded joint Designation ZS1	PM1	Figure 3	Ferritic-bainitic structure. No discontinuities or micro-cracks are observed in the structure. Bainitic areas: class I/II, precipitates: class A. Damaging processes: class 0. CLASS 2, EXHAUSTION DEGREE: approx. 0.3 ÷ 0.4.	173
	PM2			169
	HAZ1		No discontinuities or micro-cracks are found in the structure.	247
	WELD			240
	HAZ2			247
Repair welded joint Designation ZS2	PM1	Figure 4	Ferritic-bainitic structure. No discontinuities or micro-cracks are observed in the structure. Bainitic areas: class 0; precipitates: class 0; Damaging processes: class 0. MATERIAL CONDITION: CLASS 0; EXHAUSTION DEGREE: ~0.	160
	PM2		Ferritic-bainitic structure. No discontinuities or micro-cracks are observed in the structure. Bainitic areas: class I/II, precipitates: class A. Damaging processes: class 0. CLASS 2, EXHAUSTION DEGREE: approx. 0.3 ÷ 0.4.	168
	HAZ1		No discontinuities or micro-cracks are found in the structure.	247
	WELD			242
	HAZ2			168

4.3. X-ray Analysis of Phase Composition of Precipitated Carbide Isolates

As a result of dissolving the matrix of the material of the examined test specimens of repair welded joints by the electrolytic method, the existing carbides were isolated. The X-ray phase analysis was carried out on the obtained carbide isolate, and the existing carbides were identified. The obtained results of the investigations of the material of test repair welded joints are summarised in Table 4.

Table 4. Phase composition of carbides in repair welded joints.

Material Condition	Phase Composition of Carbides	Precipitation Sequence
As-received condition 14MoV6-3 steel	M_3C MC	M_3C + MC
14MoV6-3 steel 169,000 h service Designation ZS1-PM1	Isovit $Cr_{23}C_6$—main phase Cementite Fe_3C VC	$M_{23}C_{6\ main\_ph.}$ + $M_3C_{\ av}$ + $MC_{\ nw}$
14MoV6-3 steel 169,000 h service Designation ZS2-PM2	Isovit $Cr_{23}C_6$—main phase Cementite Fe_3C VC	$M_{23}C_{6\ main\_ph.}$ + $M_3C_{\ av}$ + $MC_{\ nw}$

The type and contribution of the revealed precipitates correspond to the exhaustion degree estimated based on the microstructure image of the examined materials of repair welded joints from low-alloy steels after operation beyond the design service time (Table 3).

The sequences of carbides (Table 4) within the examined materials formulated based on the X-ray diffraction analysis of electrolytically isolated carbide deposits confirm the class of microstructure as determined based on the analysis of its observed images.

4.4. Hardness Evaluation of Repair Welded Joints

Hardness measurement was taken by Vickers HV10 method on the transverse metallographic microsection of the examined repair circumferential welded joints made from materials after long-term service, marked ZS1, and material in the as-received condition and after long-term service marked ZS2. The HV10-hardness measurement results against the background of the macro photograph showing a cross-section of the repair welded joints in the examined test specimens are presented in Figure 5.

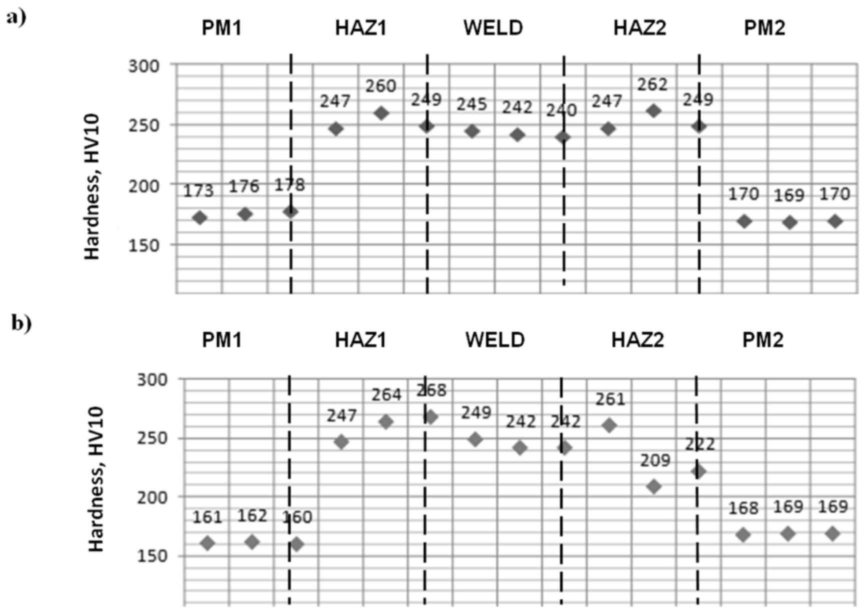


Figure 5. Distribution of the results of HV10 hardness measured on transverse microsections of the repair welded joint made from 14MoV6-3 steel. Test location—transverse microsection: (**a**) ZS1; (**b**) ZS2.

Hardness for all the examined components of repair welded joints is lower than the maximum permitted one, which is 350 HV10 for joints in the as-received condition and ranges from 160 to 179 HV10 for the parent material, from 209 to 268 for the heat-affected zone and from 240 to 249 HV10 for the weld material. This suggests that the examined welded joints were properly heat-treated after welding and will be able to transfer the required considerable loads, including those that occur during water pressure tests, shut-downs and start-ups. Hardness measurements have also shown no sudden changes when passing through the individual zones of the joint. Hardness for the 14MoV6 steel repair circumferential welded joint made from materials after 169,000 h service is, on average, 173 HV10 for the parent material, while in the weld it increases up to 262 HV10. Hardness for the 14MoV6 steel repair circumferential welded joint made from a material in the as-received condition and after 169,000 h service is, on average, 165 HV10 for the parent material, while in the weld it increases up to 268 HV10.

4.5. Abridged Creep Tests

The abridged creep tests were carried out for five test temperature levels ranging between 600 °C and 680 °C at 20 °C intervals with constant test stress σ_b = const corresponding to the operating one, which allows for obtaining test results within several months. This provides a good estimate of residual life t_{re} as it was verified in [17,18].

The method used to reduce the duration of creep tests involves accelerating the creep process by increasing the test temperature T_b well over the temperature level T_e suitable for operation in the samples maintained at a constant test stress corresponding to the operating one $\sigma_b = \sigma_r$ = const. They allow for the plotting of a straight line inclined at the time to rupture the t_r axis. The residual life is determined by extrapolation of the obtained straight line towards a lower temperature corresponding to the operating one T_e.

The results of creep tests for the examined repair welded joints marked ZS1 and ZS2 are summarised in Table 5 and presented in comparative graphs (Figure 6) as $\log t_z = f(T_b)$ at σ_b = const, where t_r is the time to rupture in the creep test.

Table 5. Results of abridged creep tests.

Test Specimen Designation	Working Parameters		Test Stress σ_b (Mpa)	Test Temperature, T_b (°C)				
	Pressure P_r (MPa)	Temperature T_r (°C)		600	620	640	660	680
				Time to Rupture, t_r (h)				
Repair welded joint made from materials after 169,000 h service Designation ZS1	-	-	50	(3127)	1197	559	234	120
Repair welded joint made from material in the as-received condition and material after 169,000 h service Designation ZS2	-	-		(3161)	1178	822	179	103
Parent material after 169,000 h service Designation PM	13.0	538	55	(286)	(1365)	559	429	196
Repair welded joint made from materials after 169,000 h service Designation ZS1	-	-		2834	672	373	189	97
Repair welded joint made from material in the as-received condition and material after 169,000 h service Designation ZS2	-	-		(2592)	1297	481	191	84

(-)—tests in progress.

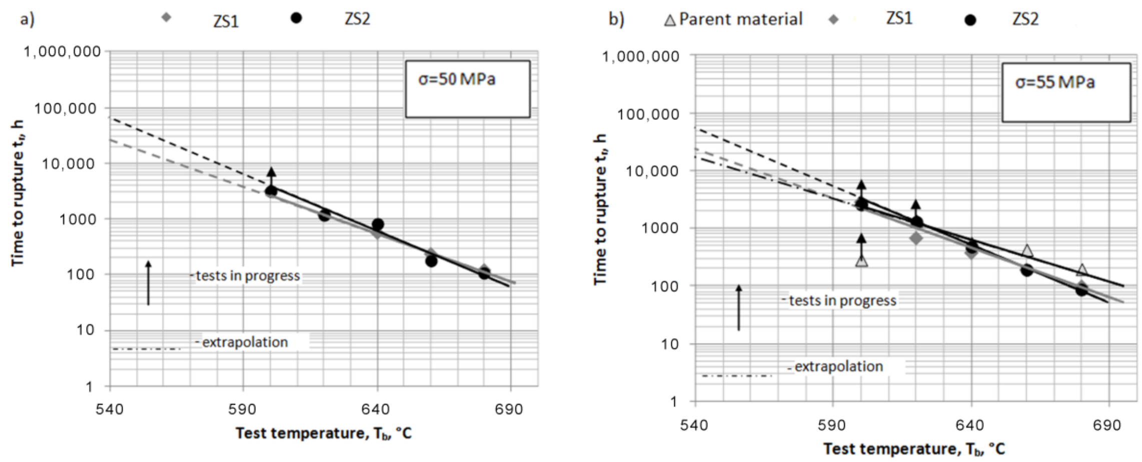


Figure 6. Result of abridged creep tests on the examined ZS1 and ZS2 repair joints and parent material in the form of $\log t_{re} = f(T_b)$ for the adopted stress level of further service (**a**) b = 50 MPa; (**b**) b = 55 MPa.

The comparison of the results of abridged creep tests in the form of $\log t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ = 50 MPa for the repair welded joint made from 14MoV6-3 steel after 169,000 h service and the repair welded joint made from 14MoV6-3 material in the as-received condition and 14MoV6-3 material after 169,000 h service is presented in Figure 6a.

The comparison of the results of abridged creep tests in the form of $\log t_r = f(T_b)$ at $\sigma_b \approx \sigma_r$ = 55 MPa for the parent material of 14MoV6-3 after 169,000 h service and the repair welded joint made from materials of 13HMF (14MoV6-3) after 169,000 h service and the repair welded joint made from 14MoV6-3 steel in the as-received condition and 14MoV6-3 steel after 169,000 h service is presented in Figure 6b.

On the basis of the previously completed creep tests, based on the extrapolation method used, the residual life (interpreted as the time to failure) was determined and the disposable residual life (being the safe time of service, which is about 0.6 of the residual life, Figure 1) was estimated as the safe time of service for the examined parent material, repair welded joint made from materials after long-term service and repair welded joint made from material in the as-received condition and after long-term service. The obtained results of extrapolation based on creep tests are summarised in Table 6 for two values of stress—50 and 55 MPa.

Table 6. Residual life determined and disposable residual life estimated by abridged creep tests of the parent material, repair welded joint made from materials after long-term service and repair welded joint made from material in the as-received condition and after long-term service.

<table>
<tr><th rowspan="2">Test Specimen Designation</th><th rowspan="2">Adopted Operating Stress σ_r (MPa)</th><th rowspan="2">Adopted Further Operation Temperature T_r (°C)</th><th colspan="2">Estimated Life Time (h)</th></tr>
<tr><th>Residual t_{re}</th><th>Disposable Residual Life t_b (about 0.6 t_{re})</th></tr>
<tr><td>Joint from materials after long-term service Designation ZS1</td><td rowspan="2">50</td><td rowspan="5">538</td><td>25,000</td><td>15,000</td></tr>
<tr><td>Joint from material in the as-received condition and material after long-term service Designation ZS2</td><td>60,000</td><td>36,000</td></tr>
<tr><td>Native material Designation PM1</td><td rowspan="3">55</td><td>20,000</td><td>12,000</td></tr>
<tr><td>Joint from materials after long-term service Designation ZS1</td><td>23,000</td><td>13,800</td></tr>
<tr><td>Joint from material in the as-received condition and material after long-term service Designation ZS2</td><td>58,000</td><td>34,800</td></tr>
</table>

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

The residual life t_{re} determined for the adopted stress level of 50 MPa for the repair welded joint of the materials after service, marked ZS1, is 25,000 h and its estimated disposable life t_b is 15,000 h (Figure 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 60,000 h and the estimated disposable life is 36,000 h.

The residual life t_{re} determined for the adopted stress level of 55 MPa for the repair welded joint of the materials after service marked ZS1, is 23,000 h and the estimated disposable life t_b is approx. 14,000 h, 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 58,000 h and the estimated disposable life is approx. 35,000 h. For the parent material after service marked PM1, the residual life is 20,000 h, and the estimated disposable life is t_b 12,000 h.

The time of further safe service of the examined new repair welded joints may be assumed to be 15,000 h for the ZS1 joint and 36,000 h for the ZS2 joint at the further service stress σ_e = 50 MPa, while for the adopted further service stress σ_e = 55 MPa the time of further safe service of the examined new repair welded joints may be assumed to be approximately 14,000 h for the ZS1 joint and approximately 35,000 h for the ZS2 joint.

5. Conclusions

1. The set of destructive materials tests presented in this paper allows for the evaluation of material condition and determination of suitability for service of repair. It is of particular importance for the operation of steam pipelines beyond the design service time.
2. The evaluation of the material condition of repair welded joints is made based on a comprehensive summary of the results of investigations on mechanical properties, microstructure and abridged creep tests. These results are in turn a part of the database of the materials' characteristics for steels and their welded joints with materials showing varying degrees of degradation. This database is used in diagnostic tests for pressure parts of boiler elements.
3. The quantitative dimension of suitability for service of the material of repair welded joints is achieved by extrapolating the straight line obtained in abridged creep tests from $\log t_r = f(T_b)$ at σ_b = const towards the temperature of assumed operation, which allows residual life t_{re} and disposable residual life t_b to be determined for the working temperature.
4. The knowledge of the share of disposable residual life $t_{b\mathrm{e}}$ in residual life t_{re} ($t_{b\mathrm{e}}/t_{\mathrm{re}}$) allows the safe time of service of the examined joints to be determined for the required performance parameters.
5. The examined repair welded joints are suitable for operation for a limited time resulting from the disposable residual life determined for defined temperature and stress parameters of further service.

The completed tests of the material of steam pipeline and welded joints have shown that long-term operation beyond the design service time does not disqualify the material from service. It has been demonstrated that the modernisation and repair works carried out on the steam pipeline materials by making welded joints show lower creep strength than the basic material. The lower strength of repair welded joints in relation to the parent material should be taken into account in design calculations while extending the service time beyond the design service life.

It has also been demonstrated that, in contrast to the microstructural investigations and the basic investigations of mechanical properties, the abridged creep tests allow the real determination of the time of further safe operation of the elements of power equipment working beyond the design service life to be obtained.

The analysis of the research results of abridged creep tests shows that, independently, of the values of the stress, creep resistance of repair welded joint ZS2 is twice as high as welded joints marked ZS1. This difference is probably related to the higher creep resistance of the parent material resulting in a higher creep resistance of joints marked ZS2.

Acknowledgments: The publication was partially financed by the statutory grant from Faculty of Mechanical Engineering, the Silesian University of Technology for the year 2016. The results in this publication were obtained as a part of research co-financed by the National Centre for Research and Development under contract PBS3/B5/42/2015—Project: "Methodology, evaluation and forecast of operation beyond the analytical operation of welded joints in pressure elements of power boilers beyond the design work time".

Author Contributions: M.S., A.Z. and M.D.-K. conceived and designed the experiments; M.D.-K. and A.Z. performed the experiments; M.M., A.J. and M.K. analysed the data; M.S. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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