Arch. Metall. Mater. **63** (2018), 2, 889-897

DOI: 10.24425/122419

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RESIDUAL LIFE OF BOILER PRESSURE PARTS MADE OF THE 13CrMo4-5 STEEL AFTER LONG-TERM OPERATION IN A CREEP CONDITIONS

This paper presents the method for determination of the time of further safe service for welded joints of boiler components after exceeding the design work time. The evaluation of the life of the parent material and its welded joints was performed. Microstructure investigations using a scanning electron microscope, investigations of strength properties, impact testing, hardness measurements and abridged creep tests of the basic material and welded joints were carried out. The investigations described in this paper allowed the time of further safe service of the examined components made of 13CrMo4-5 steel to be determined. The method for determination of the time of safe service of boiler components working under creep conditions allows their operation beyond the design service life. The obtained results of investigations are part of the materials database developed by the Institute for Ferrous Metallurgy.

Keywords: 13CrMo4-5 steel, Microstructure, Residual life, Welded joints, Mechanical properties

1. Introduction

More than 90% of power units operating in Poland have exceeded their design service life of 100,000 h, which results from temporary creep strength used for calculations. Most of the units have even exceeded 200,000 h of service. Decisions to extend the operation beyond the design time of 100,000 h were taken by using the calculation method based on data of temporary creep strength for the time of 200,000 h and positive results of comprehensive testing, especially that of the critical components in the pressure section of boilers and turbines [1-7]. Out of these components, those working above the limit temperature, i.e. under creep conditions, are crucial. In the evaluation of these components, it is important and necessary to evaluate the condition of their materials. The evaluation is performed based on obtained results of non-destructive or destructive materials testing for which the set of research methods is selected depending on component accessibility, actual service time and the possibility of sampling the material for destructive testing. The comparison of obtained results to possessed characteristics of materials after service allows for good evaluation of the material condition and exhaustion degree and determination of the time of further safe service until the next inspection [8-17]. However, reaching the level of 200,000 h service requires not only a good estimation of residual life but also its determination based on destructive testing on a representative test specimen taken for testing. It is not always possible in practice. However, it can be carried out while evaluating the material condition of the main steam pipeline or force pipeline, headers and desuperheaters as well as steam superheater coils. Nevertheless, it must be preceded with an economic calculation of cost-effectiveness for such a procedure.

An equally important, if not the most important, issue related to the life of structural elements of power systems is service life of welded joints as well as repair welded joints made of materials after service with materials in the as-received condition or materials after service. This, in turn, requires the knowledge of the behaviour of the materials of examined welded joints under conditions corresponding to the operating ones and the knowledge of technology for repairing welded joints [18-24].

The method for determination of residual life and disposable residual life of 13CrMo4-5 components after long-term service under creep conditions is discussed below, and the presented results of investigations are the only study on researching the 13CrMo4-5 welded joints after service including determination of the time of their safe service that has been previously known to the authors.

The main feature of a material which determines its suitability for operation under creep conditions is temporary creep strength. Creep resistance at a constant temperature and a con-

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stant load is corresponded by the time to rupture, which is defined as the lifetime t_r [25-30].

In practice, in addition to the life time, the concept of residual life t_{re}, which relates to the extension of the time of safe service of power system components working under creep conditions, especially beyond the design service time, is also used frequently. It is defined as a difference in time between the practical time to rupture t_r and the real time of service t_e, i.e. $t_{re} = t_r - t_e$. However, the determination of residual life is not sufficient to determine the time of safe service. Therefore, the concepts of disposable life t_b and disposable residual life t_{be} were introduced. The disposable life t_b (t_{be}) is a part of the lifetime t_r (t_{re}). The value of this life time is the time corresponding to the end of viscous creep of the examined material [1]. The graphic presentation of the definition of life, residual life and disposable life is shown in Fig. 1.

The subject of the study below is the evaluation of the condition of the basic material and circumferentially welded joints of the critical components of low-alloy steel boilers after long-term service under creep conditions beyond the design work time of 100,000 h and their suitability for further service.

The original value of this paper is the determination of residual life and disposable residual life for welded joints of 13CrMo4-5 components after long-term service based on abridged creep tests about the investigations of microstructure and mechanical properties. The performance of the following investigations is to ensure safe service and availability of pressure components of steam boilers operated beyond the design service time, and for modernised boilers, it is to provide enhanced efficiency including the fulfilment of applicable environmental requirements.

2. Material for investigations

Based on the diagnostic tests and measurements, including nondestructive materials testing on industrial facilities and operating experiences, the primary steam pipeline and the second-stage secondary steam superheater header (RH2) were selected out of the examined 13CrMo4-5 (15HM) components and test specimens for investigations, along with a peripheral welded joint after long-term service, were taken from them (Fig. 2).

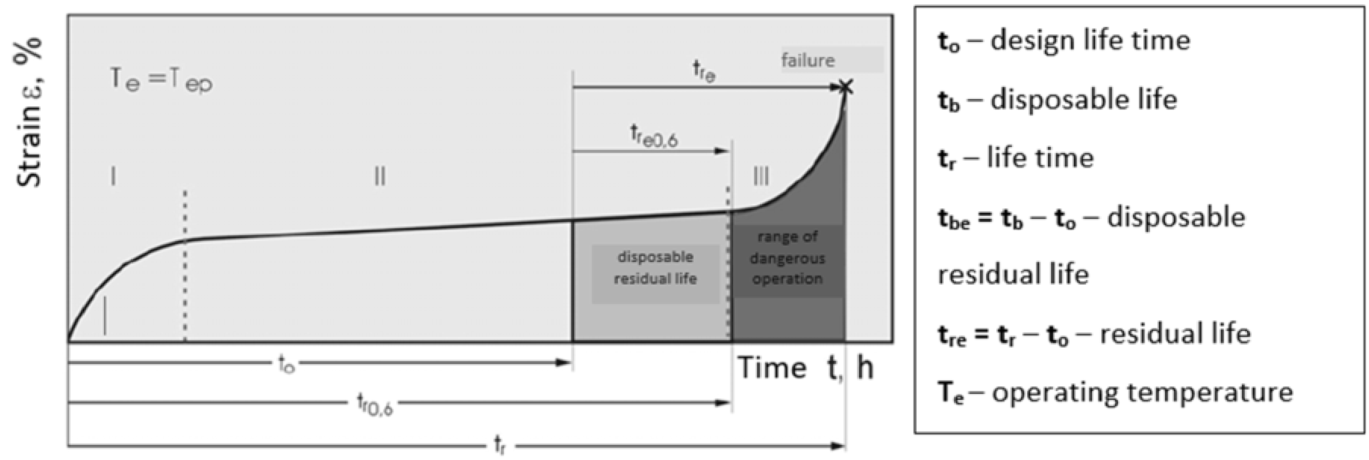
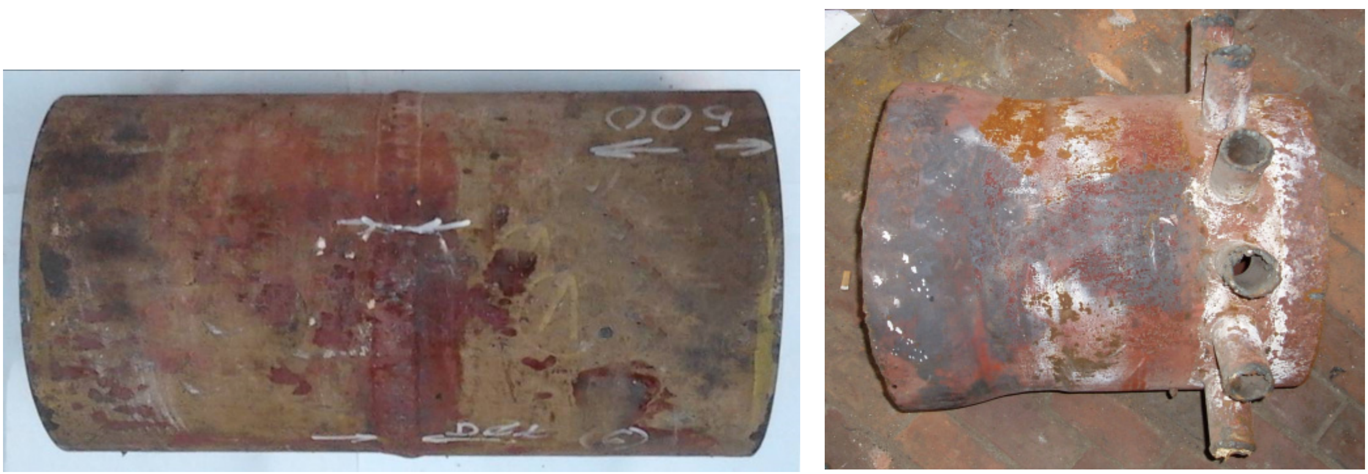


Fig. 1. Graphic presentation of the definition of life, residual life and disposable life



a) b)

Fig. 2. Material for investigations as a test specimen of: a) primary steam pipeline after more than 200,000 h service; b) RH2 header (second-stage secondary steam superheater) after 150,000 h service, consisting of the parent material and circumferential weld joint

The materials testing of test specimens included:

- chemical composition analysis with a spark atomic emission spectrometer,
- microstructural investigations by scanning microscopy with Inspect *F* microscope,
- investigations of mechanical properties at room and elevated temperatures:
  - static tensile test with Zwick testing machine with max. load of 200 kN to determine tensile strength R_m, yield point R_e, R_e^t, elongation A_5 and reduction in area *Z*,
  - Charpy V-notch impact testing,
  - Vickers hardness measurement (HV10),
  - abridged creep tests without measurement of elongation during the test to determine the material's residual life.

The results of check analysis of chemical composition of individual examined components and welded joints compared to the requirements of the standard for 13CrMo4-5 steel are presented in Table 1.

The examined materials of the primary steam pipeline and RH2 header test specimens meet the requirements of the standard for chemical composition of the examined 13CrMo4-5 (15 HM) steel grade according to EN 10216-2. The chemical analysis of the primary steam pipeline weld material is slightly different from the requirements for 13CrMo4-5 steel. Slightly lower carbon content was probably selected to obtain the weld performance similar to that of the parent material.

3. Evaluation of mechanical properties and microstructure of the material for investigations

To properly evaluate the condition of the material, i.e. exhaustion degree based on changes in the microstructure of analysed material, such investigations should be performed using scanning electron microscopy with magnifications of up to 5,000× and suitable resolution of obtained microstructure images. The knowledge of the behaviour of examined materials at the time of service under creep conditions is also required. The research performed by the Institute for Ferrous Metallurgy in Gliwice (Poland) for many years has allowed concluding that changes in the microstructure occur in its primary phase components and the existing precipitates, resulting in formation and development of internal damages. It has been found that the contribution of individual processes and their intensity depends on the stature type, initial state and exhaustion degree. Initially, the biggest changes are related with the disintegration of pearlite and/or bainite areas, and as the exhaustion degree increases, the intensity of these changes decreases, whereas the intensity of precipitation processes increases. The advanced state of development of precipitation processes promotes the initiation and development of internal damages resulting in discontinuities [13-16].

To estimate and determine the time of safe service for the material of critical components of pressure equipment working under creep conditions after exceeding the design work time, the knowledge of residual creep strength is necessary. As each system has to be shut down from time to time (planned and unplanned shut-downs) and put to periodic repairs, it is necessary to perform water pressure tests to check the system for tightness and ability to transfer loads at the test temperature. Therefore, in addition to residual creep strength, the knowledge of the basic strength and plastic properties of the materials and welded joints after long-term service is important. Also, the knowledge of the value of elongation determined by tensile test and the value of impact energy obtained in impact test is important from deformability of the materials and welded joints under service conditions. The knowledge of the value of impact energy makes it possible to adopt in industrial practice the appropriate temperature of water pressure tests as well as boiler start-up and shut-down conditions, by condition of these materials after long-term service. Important information is also the brittle fracture appearance transition temperature. This temperature corresponds to fractures obtained in impact test with the similar percentage of ductile and brittle fracture (50/50%). In practice, it is assumed that this condition corresponds to impact energy of 27J, obtained on standard V-notched test specimens [13-18].

Long-term service under creep conditions also results in a change in hardness level of examined materials [13].

However, out of all the mechanical properties, the most important ones who determine the suitability for operation under creep conditions are the properties determined as a result of creep tests. Creep strength, which is the basis for design calculations, determines the ability of the components made of the examined materials to carry the operational loading. Long-term service of each of the examined components reduces the temporary creep strength. It cannot be less than 20% of the average value adopted for calculations for the assumed required time of service. Creep tests are so far the only known method for determination of service life for the actual operating parameters which are in

TABLE 1

Chemical composition analysis of materials of examined 13CrMo45 (15HM) components after long-term service under creep conditions

Component	Content of elements, %									
	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Al
Primary steam pipeline test specimen	0.15	0.60	0.25	0.020	0.017	0.097	0.99	0.20	0.51	0.002
Pipeline weld	0.080	0.65	0.32	0.018	0.016	0.064	0.91	0.068	0.49	0.003
RH2 header test specimen	0.15	0.58	0.23	0.025	0.016	0.055	0.89	0.096	0.43	0.013
RH2 header weld	0.12	0.59	0.30	0.021	0.015	0.051	0.88	0.093	0.041	0.011
To EN 10216-2	0.10-0.17	0.40-0.7	max. 0.35	max. 0.025	max. 0.020	max. 0.30	0.70-1.15	max. 0.30	0.40-0.60	max. 0.040

operation. In these tests, the decisive factor that determines their duration is the time to rupture. In the assessment of specific material, both in the as-received condition and after service, it is possible to reduce the duration of the tests. However, the research methods used for this purpose have to be verified with results of long-term creep tests [1].

3.1. Microstructural investigations

The microstructural investigations were carried out on metallographic microsections. The microsections made on the cross-section of test specimens of the examined components in the area of weld were prepared by mechanical grinding and polishing followed by etching. Observations were performed with scanning electron microscope Inspect F.

The test results in the form of the microstructure images of the material of primary steam pipeline after more than 200,000 h service are shown in Fig. 3a, while the microstructure image of the circumferential welded joint, and in particular of the heat affected zone on the left and right-hand side of the weld and the material of weld, is shown in Fig. 3b. The test results in the form of the microstructure images of the material of RH2 header after 150,000 h service are shown in Fig. 4a, while the microstructure image of the circumferential welded joint, and in particular of the heat affected zone on the left and right-hand side of the weld and the material of weld, is shown in Fig. 4b.

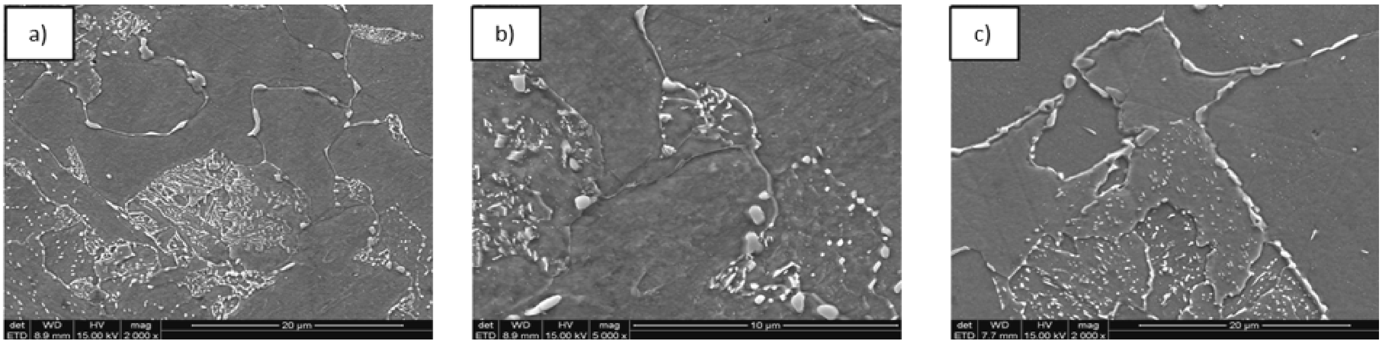
The parent material of the steam pipeline (Fig. 3a) (left and right side) was characterised by the ferritic microstructure with pearlite and bainite areas, which due to the long-term impact of temperature and stress were partially degraded, revealing the disappearance of the lamellar microstructure of pearlite and coagulation of precipitates in bainitic areas. Few very fine precipitates within the ferrite grains were also visible, whereas, at the grain boundaries, numerous fine precipitates forming chains in places were observed. The heat-affected zones of the examined joint were characterised by a fine-grained bainitic-ferritic microstructure with numerous precipitates at and within the grain boundaries (Fig. 3b).

Similarly to the steam pipeline's material (Fig. 3a), the parent material of the RH2 steam header (Fig. 4a) (left and right side) was also characterised by the ferritic microstructure with pearlite and bainite areas. However, the bainite/pearlite areas were characterised by a lower degree of degradation. A slight decomposition of the lamellar microstructure of pearlite and the coagulation of precipitates within the bainite areas was visible only. Within the ferrite grains, single very fine precipitates were observed, whereas, at the grain boundaries, single fine precipitates were observed. In the heat-affected zone of the examined header joint, fine-grained microstructure, mostly with very fine precipitates at the grain boundaries, was observed (Fig. 4b).

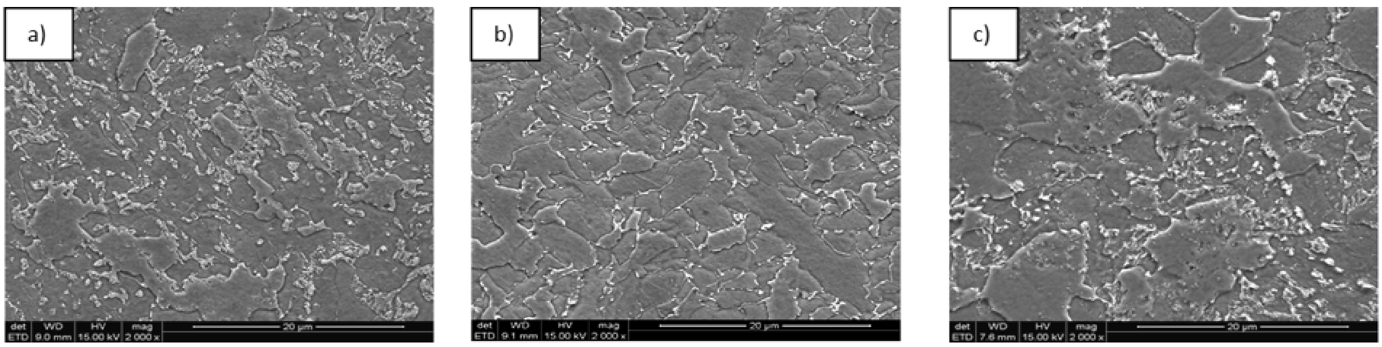
The microstructure description including the evaluation and the exhaustion extent t_e/t_r estimated based on the own Institute for Ferrous Metallurgy's classification is provided in Table 2.

3.2. Evaluation of mechanical properties

For test specimens of the primary steam pipeline and RH2 header as well as their welded joints after long-term service

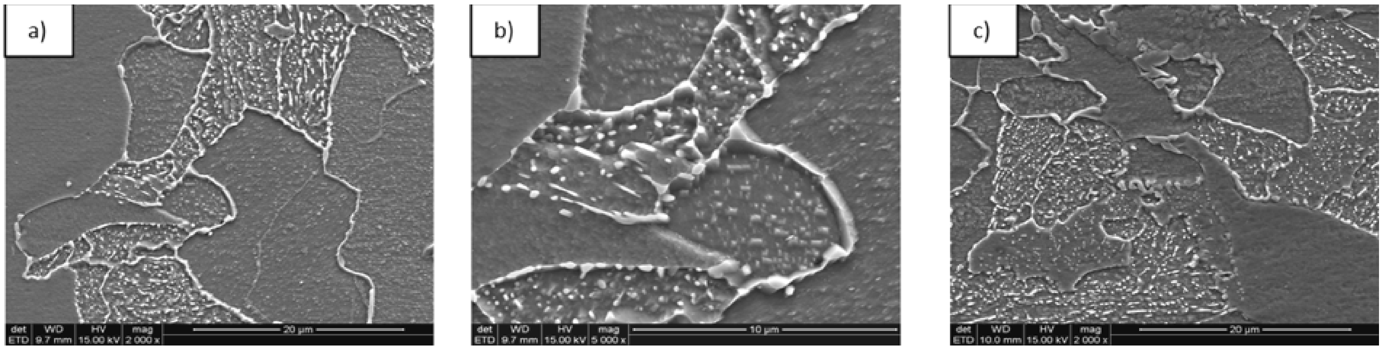


a)

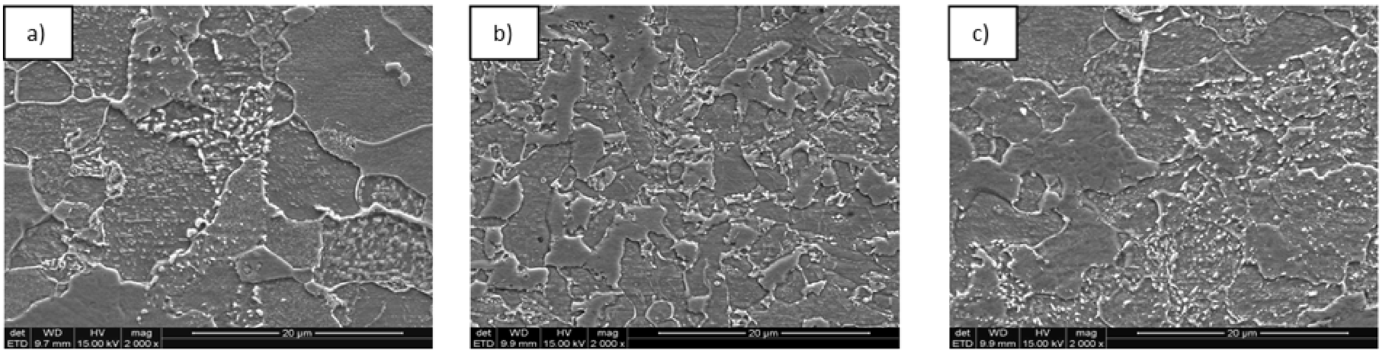


b)

Fig. 3. Structure of the material of test specimen at circumferential welded joint of the 13CrMo4-5 primary steam pipeline after more than 200,000 h service, observed with a scanning electron microscope a) and b) parent material – left-hand side; c) parent material – right-hand side



a)



b)

Fig. 4. Structure of the material of test specimen at circumferential welded joint of the 13CrMo4-5 RH2 header after 150,000 h service, observed with a scanning electron microscope: a) and b) parent material – left-hand side; c) parent material – right-hand side

TABLE 2

Evaluation of the results of structure investigations on test specimens of the primary steam pipeline and RH2 header with circumferential welded joint after long-term service under creep conditions

Component	**Description of structure** **Material condition – exhaustion degree**	**HV10**
Primary steam pipeline after more than 200,000 h service	Ferritic-pearlitic-bainitic structure. No discontinuities and micro-cracks are observed in the structure. Pearlitic areas: class I, precipitates: class a/b Damaging processes: class O CLASS 2, EXHAUSTION DEGREE: approx. 0.3÷0.4	148÷151
Primary steam pipeline weld after more than 200,000 h service	Bainite with small amount of ferrite. Significant amount of precipitates: within the bainitic areas – in various sizes, in ferrite – fine and fairly evenly distributed. No discontinuities and micro-cracking are found within the HAZ structure.	181÷206
RH2 header after 150,000 h service	Ferritic-pearlitic structure. No discontinuities and micro-cracks are observed in the structure. Pearlitic areas: class I, precipitates: class o/a Damaging processes: class O CLASS 1, EXHAUSTION DEGREE: approx. 0.2÷0.3	146÷155
RH2 header weld after 150,000 h service	Bainite with small amount of ferrite. Significant amount of precipitates: within the bainitic areas – in various sizes, in ferrite – fine and fairly evenly distributed. No discontinuities and micro-cracking are found within the HAZ structure.	180÷201

under creep conditions, the evaluation of strength properties under room and elevated temperature and impact strength was performed.

Strength tests

The investigations of strength properties were carried out as part of the tensile test at room temperature and the elevated temperature similar to the operating one. The comparison of obtained results of investigations on tensile strength (R_m, R_m^t) depending on test temperature is shown in Fig. 5a and on yield point (R_e, R_e^t) is shown in Fig. 5b for the examined materials of 13CrMo4-5 (15HM) primary steam pipeline and RH2 header test specimens after long-term service.

The analysis of the results of mechanical tests, obtained in the static tensile test at room and elevated temperature close to the long-term operation temperature of the examined components, shows that the properties of both the material of the steam pipeline and the material of the steam superheater's RH2

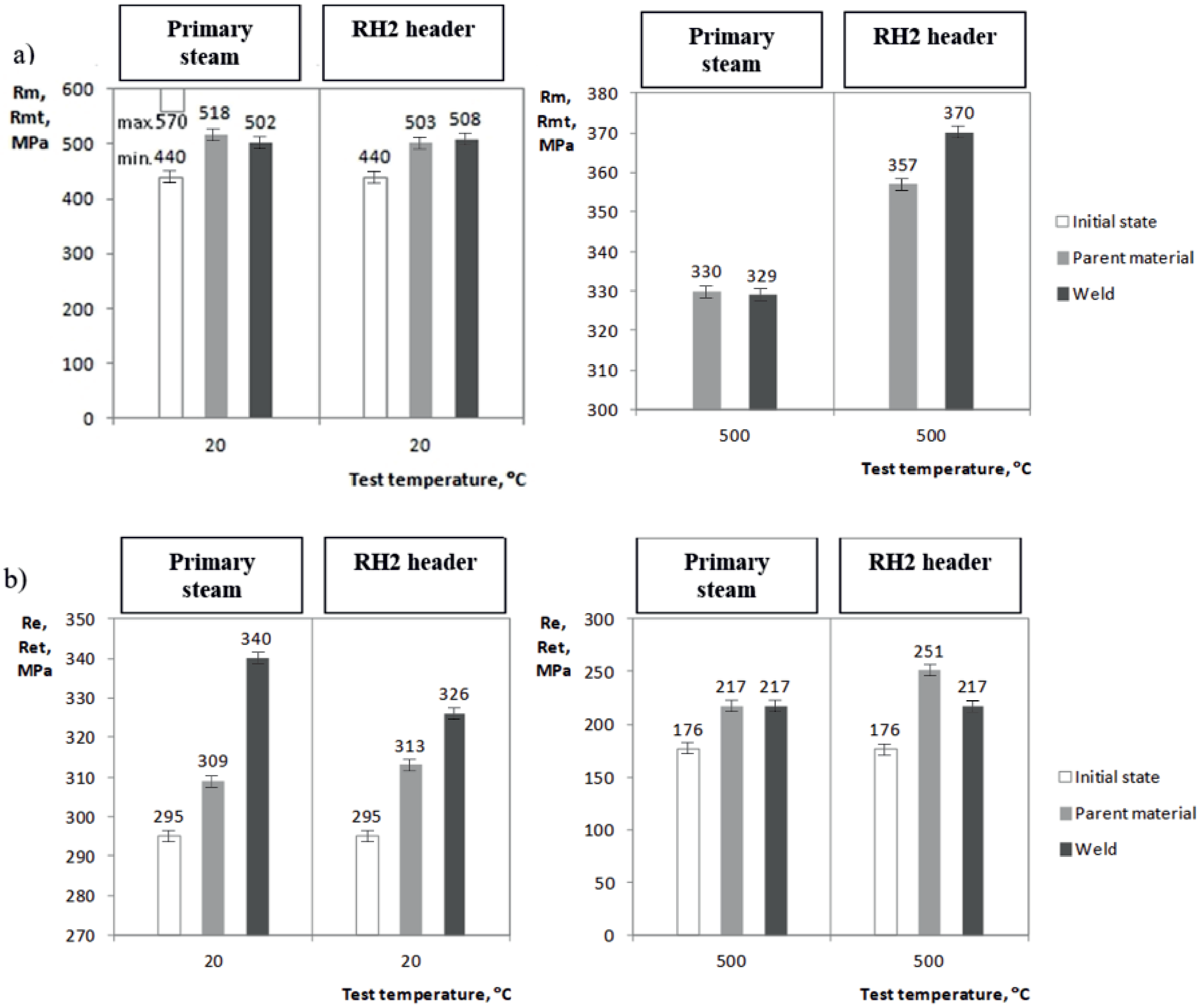


Fig. 5. Comparison of the results of investigations of mechanical properties of the primary steam pipeline and RH2 header test specimens after 200,000 h service under creep conditions, at room and elevated temperature: a) tensile strength; b) yield point

header are higher than the minimum properties required for 13CrMo4-5 steel in the as-received condition. Yet, their loss cannot be determined unambiguously, as there are no results of acceptance tests available for these materials.

Impact tests

Impact tests were carried out on longitudinal test specimens with the V-notch perpendicular to the surface of the examined elements of the primary steam pipeline and RH2 header test specimens after long-term service. The longitudinal test specimens were broken with Mohr-Federhaff impact testing machine with the maximum impact energy of 294J. The tests were carried out within the temperature range from 0 to 60°C. The values of temperature were selected for the examined component from case to case. The comparison of the obtained test results and curves made for the material of pipeline and header and the element of the circumferential weld joint from 13CrMo45 (15HM) steel are shown in Fig. 6a and 6b, respectively.

The nil ductility transition temperature of the examined components of the primary steam pipeline is approx. +40°C, while for the weld it is approx. +15°C. The brittle fracture appearance temperature of the RH2 header is +60°C, while for the weld it is above +60°C.

The obtained results of impact tests indicate that there is no correlation between the impact energy and the degree of degradation of microstructure and strength properties of 13CrMo4-5 steel. In contrast, the high values of brittle fracture appearance temperature of the examined components and their welded joints show the need to take them into account when starting up and shutting down the boiler.

Abridged creep tests

The abridged creep tests were carried out for 5 test temperature levels ranging between 600 and 680°C at 20°C intervals with constant test stress σ_b = const corresponding to the operating one.

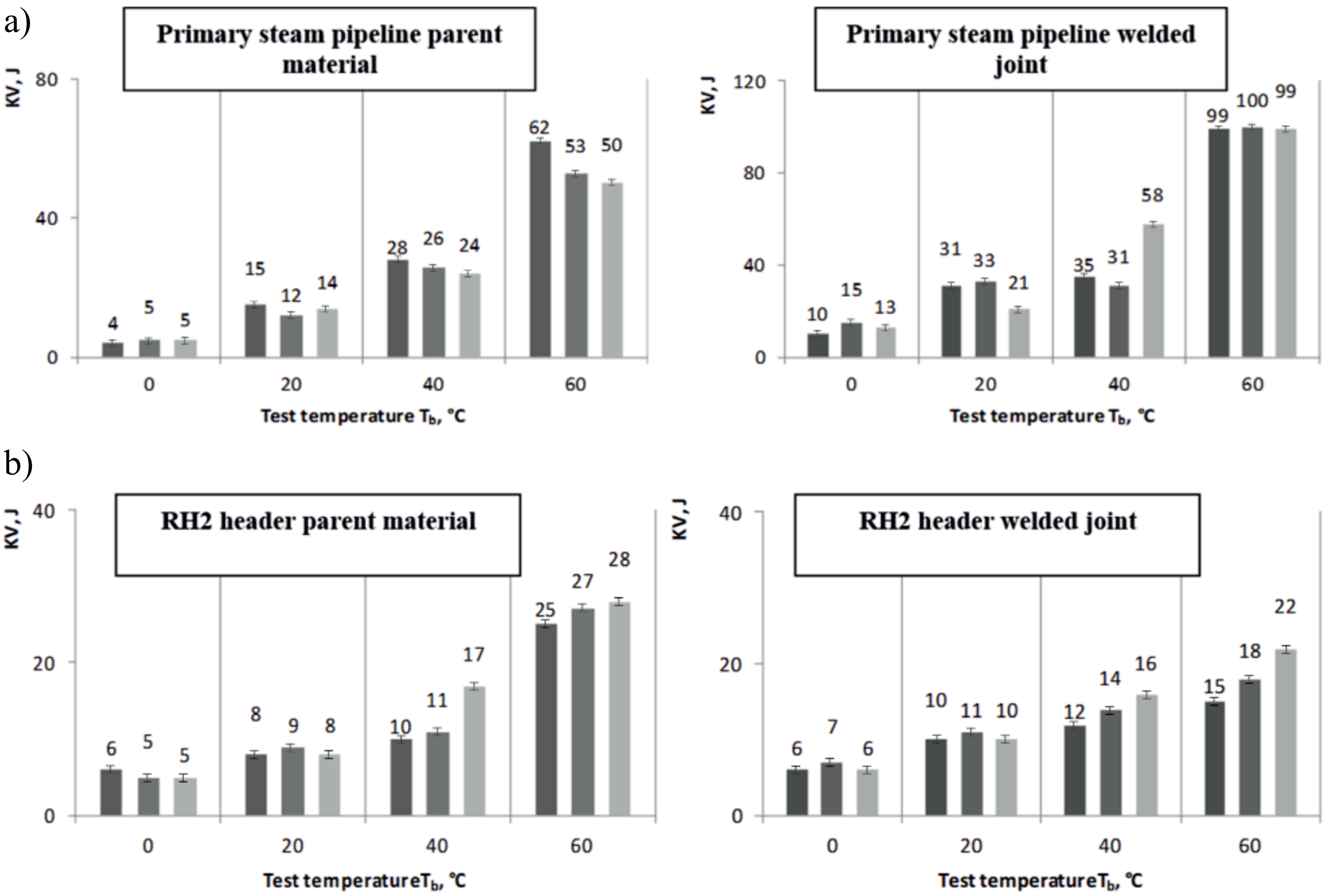


Fig. 6. Comparison of impact strength results for the material of test specimens and circumferential welded joint of: a) the primary steam pipeline and b) RH2 header after long-term service under creep conditions

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

The results of creep tests for the examined materials and circumferentially welded joints are shown in comparative graphs (Fig. 7a,b) as $\log t_z = f(T_b)$ at $\sigma_b =$ const, where t_z is the time to rupture in the creep test.

The obtained results of abridged creep tests allowed the residual life of the examined materials and circumferentially welded joints of the examined pipeline and header test specimens after long-term service under creep conditions to be determined by extrapolation.

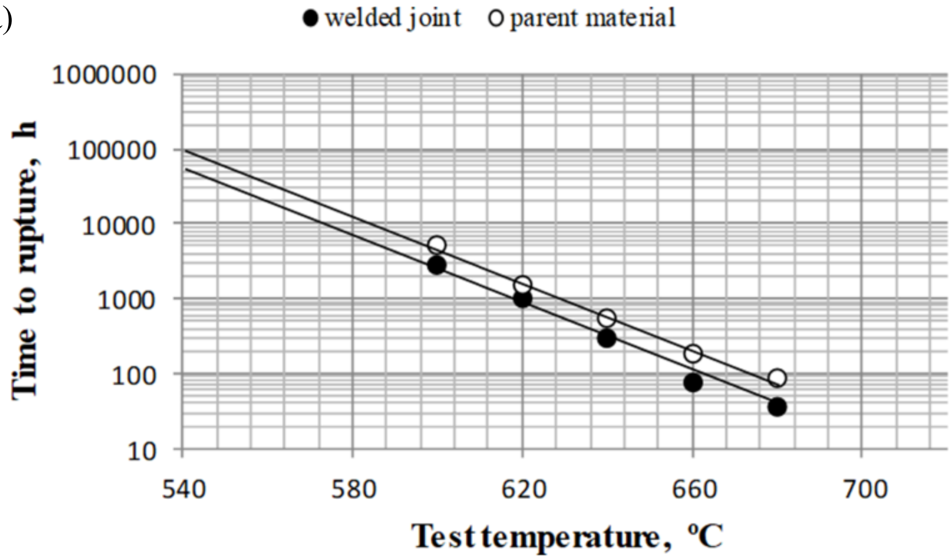
On this basis, the disposable residual life was estimated for working parameters of further service, which the life determines the maximum time of further safe service of the examined components (Table 3).

TABLE 3

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

No.	Steel grade test specimen designation	Material for investigations Dimensions $D_z \times g_n$ [mm]	Adopted operating stress σ_r [MPa]	Adopted further operation temperature T_r [°C]	Estimated life time [h] Residual t_{re}	Estimated life time [h] Disposable residual t_b
1	13CrMo45 Primary steam pipeline material	273 × 22	60	540	110,000	61,000
2	Primary steam pipeline welded joint			540	85,000	47,000
3	13CrMo45 RH2 header material	410 × 20	60	540	180,000	100,000
4	RH2 header welded joint			540	130,000	72,000

a)



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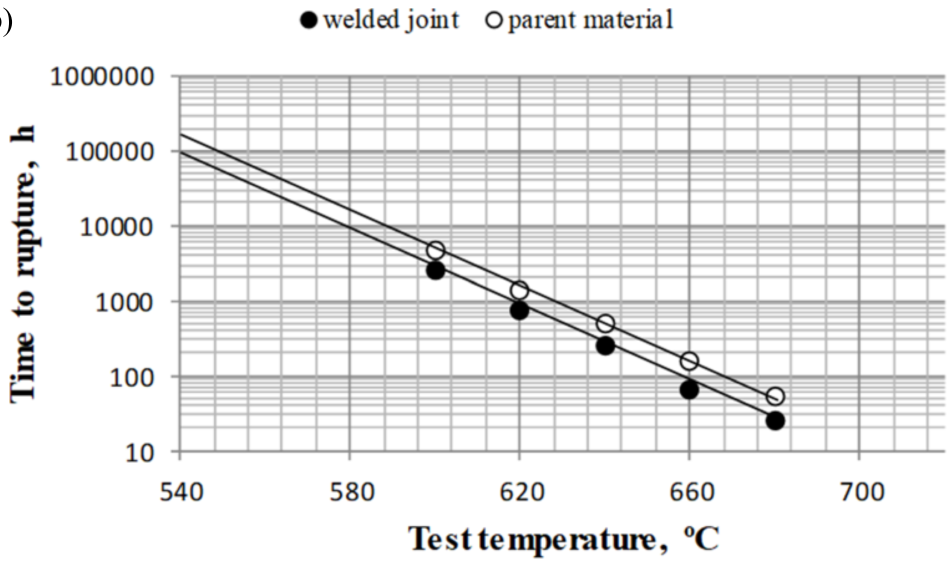

Fig. 7. Disposable residual life t_{be} for test stress in function of working temperature level T_{ep}; a) for material and circumferential weld joint of primary steam pipeline after more than 200,000 h service; b) for material and circumferential weld joint of RH2 header after 150,000 h service

4. Conclusions

The following conclusions can be drawn based on the obtained results of investigations and their analysis:

1. Changes in the image of the microstructure of the examined materials of pipeline and header show their diverse degradation due to long-term service under creep conditions. In its form, the microstructure of the header is only slightly different from the as-received state of the examined steel, while the microstructure of the steam pipeline's knee consists of ferrite with mostly coagulated pearlite and bainite areas. Rather numerous precipitates of various sizes, forming chains in places, can be seen at the ferrite grain boundaries. In the weld of the examined welded joints, the microstructure of bainite with ferrite and with precipitates at the grain boundaries was observed.
2. No initiation of internal damage processes and no microstructure discontinuities were found in the material of all the examined components and their circumferential welded joints.
3. The obtained results of investigations on tensile strength and yield point at room and elevated temperature of the material of primary steam pipeline and RH2 header meet the requirements for the material in the as-received condition according to EN 10216-2.
4. The obtained results of investigations of strength properties of the primary steam pipeline and RH2 header circumferential welded joint meet the requirements for the material in the as-received condition according to EN 10216-2.
5. The impact resistance measured on V-notched test specimens does not meet the requirements for pipes in the as-received condition according to EN 10216-2. The brittle fracture appearance transition temperature of the examined test specimens of the primary steam pipeline and RH2 header components is positive and equals to +40°C and +60°C, respectively, whereas the brittle fracture appearance

transition temperature of the weld material, compared to that of the parent material, is shifted to a lower temperature for the primary steam pipeline, while for the RH2 header it is shifted to a higher temperature, and equals to +15°C and above +60°C, respectively.

6. The procedure presented allows the time of further safe service beyond the design service life to be determined based on abridged creep tests carried out at a temperature higher than the operating one for the required parameters of further service.
7. The residual life determined during the abridged creep tests for working temperature T_r = 540°C and working stress σ_r = 55 MPa of the primary steam pipeline is respectively: for pipeline material – 110,000 h and for the welded joint of this pipeline – 85,000 h.
8. The residual life determined during the abridged creep tests for working temperature T_r = 500°C and working stress σ_r = 55 MPa of the RH2 header is respectively: for header material – 180,000 h and welded joint of this header – 130,000 h.
9. The disposable residual life, which is the time of further safe service for the above-mentioned parameters, is respectively: of pipeline material – 61,000 h and for the welded joint of the pipeline – 47,000 h, as well as for header material – 100,000 h and welded joint of the header – 72,000 h. In both cases, regardless of the exhaustion degree of parent material of the examined components, the life of the welded joint is lower by about 30% than that of the basic material.
10. The characteristics of creep strength determined based on the transformation of the results of abridged creep tests allow the residual life to be determined for a set of working parameters of any choice (σ_r, T_r) existing under industrial conditions.

Acknowledgement

This publication was co-financed by the Ministry of Science and Higher Education of Poland as the statutory financial grant of the Faculty of Mechanical Engineering SUT. The published results were obtained as part of the research co-financed by the National Science Centre under contract no. PBS/B5/42/2015 – Project: "Methodology, assessment and forecast about the operation of welded joints in pressure elements of power boilers beyond the design work time".

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