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Creep Characteristics of Engineering Materials

Janusz Dobrzański and Adam Zieliński

Abstract

The assessment of suitability for further service of the basic material and circumferential welded joints of primary steam pipelines made of 14MoV6-3 steel was made based on the determined characteristics of their mechanical properties and structure. The tests were carried out on materials after service significantly exceeding the design time and 200,000 h. The mechanical properties with respect to the determined class of structure for the basic and welded joint material were compared to the determined class of damage in accordance with the Institute for Ferrous Metallurgy's own classification of the condition of materials after service under creep conditions. The residual life and disposable residual life were determined based on short-term creep tests and referred to the class of existing structure and the class of damage. The assessment of the suitability of the basic and circumferential welded joint material for further service was made.

Keywords: creep, welded joint, Cr-Mo-V steel, microstructure, residual life

1. Introduction

In the European conventional power generation, a small number of newly constructed units have been recorded in at least several recent years, which is caused by, but not limited to, a lot of factors related mainly to environmental protection. Therefore, the electricity producers direct their main efforts at maintaining the availability of existing power units while ensuring their safe service. The inspections of and repairs to the energy installations that are in use and whose design service life was in most cases significantly exceeded while at the same time providing the reliable efficient diagnostics seem to be the proper way for the achievement of these objectives.

However, the performance of periodic inspections and repairs is not sufficient to maintain the current level of electricity and heat production in Poland. The modernisation of the units being operated is required as well. To maintain the current level of production, it is estimated that each year the modernisation of units with a total capacity of at least 2000 MW is necessary. Therefore, the important issue to be resolved has become not only the condition assessment of the pressure section of boiler and forecast about its further safe service but also the design modernisation with selection and use of new materials allowing for construction and installation of new components [1–10]. The required increase in efficiency and extension of service time of the operating high-power units, i.e. 200, 360 and 500 MW, far beyond the design time up to the expected min. 350,000 h involves the need to replace certain components because of the end of their life and to modernise them. Certain critical components being replaced are often made of new-generation steel for the power

generation industry [11–20]. At the same time, these units are expected to be operated in the control system and to comply with standards of the European directive on limitation of harmful emissions into the atmosphere.

As part of the diagnostics, it is necessary to perform the condition assessment not only for the basic material of the components working under creep conditions but also for the material of welded joints. The condition assessment of the welded joint material is necessary to determine the ability of the components to transfer the required service loads during their further service [21–34].

If there is a need to repair or replace a part or entire component with a new one, the capability of the basic material of the operated component to make such a repair or replacement should be determined. When condition of this material after service allows a repair, it is necessary to develop the repair technology from time to time.

The subject matter of the testing, including non-destructive and destructive tests, related to the long-time operated and repair welded joints of materials after long-term service with materials after service or with new materials is a separate issue dealt with by the Institute for Ferrous Metallurgy for many years.

The developed and applied research methods and the adopted procedure allow for the correct condition assessment of the basic material and welded joint material (HAZ and weld). The test results for long-time operated as well as repair and modernisation welded joints obtained so far allowed expanding the material database with such data and proposing the procedure for making such welded joints when necessary.

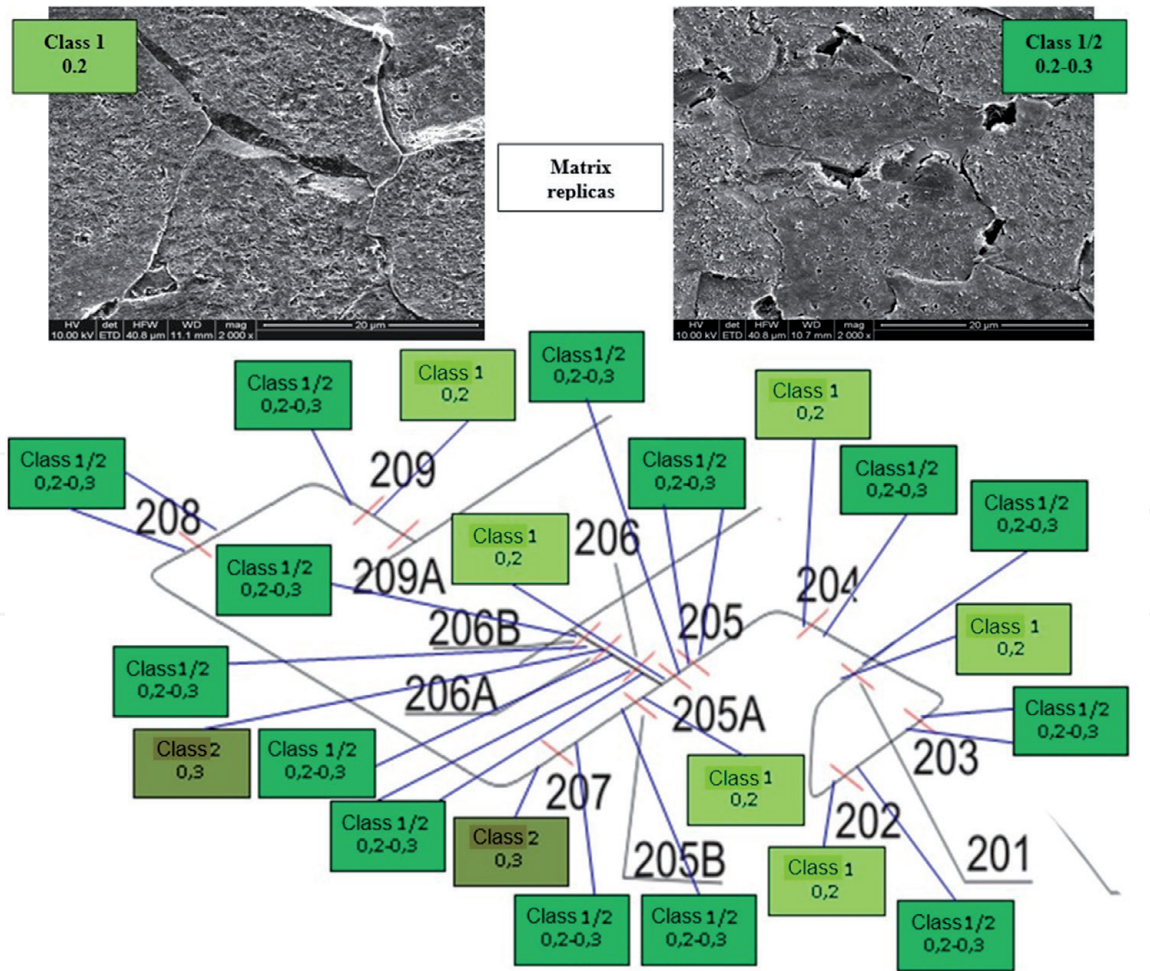


Figure 1.
The class of microstructure and exhaustion degree of the material of straight connection pipes (before the weld at the inlet side and after the weld at the agent outlet side) of the section of 200 MW primary steam pipeline unit boiler after 220 h service under creep conditions.

2. Condition assessment of the material of welded joints in components operated beyond the design time by non-destructive methods

The criterial element deciding about the suitability for further service of butt-welded joints of components operating under creep conditions is the exhaustion degree of basic materials determined based on the revealed state of microstructure and its determined class as well as the degree of internal damages and the class of damages of the heat-affected zone (HAZ) and weld material. The example of the results of non-destructive tests on microstructure of the primary

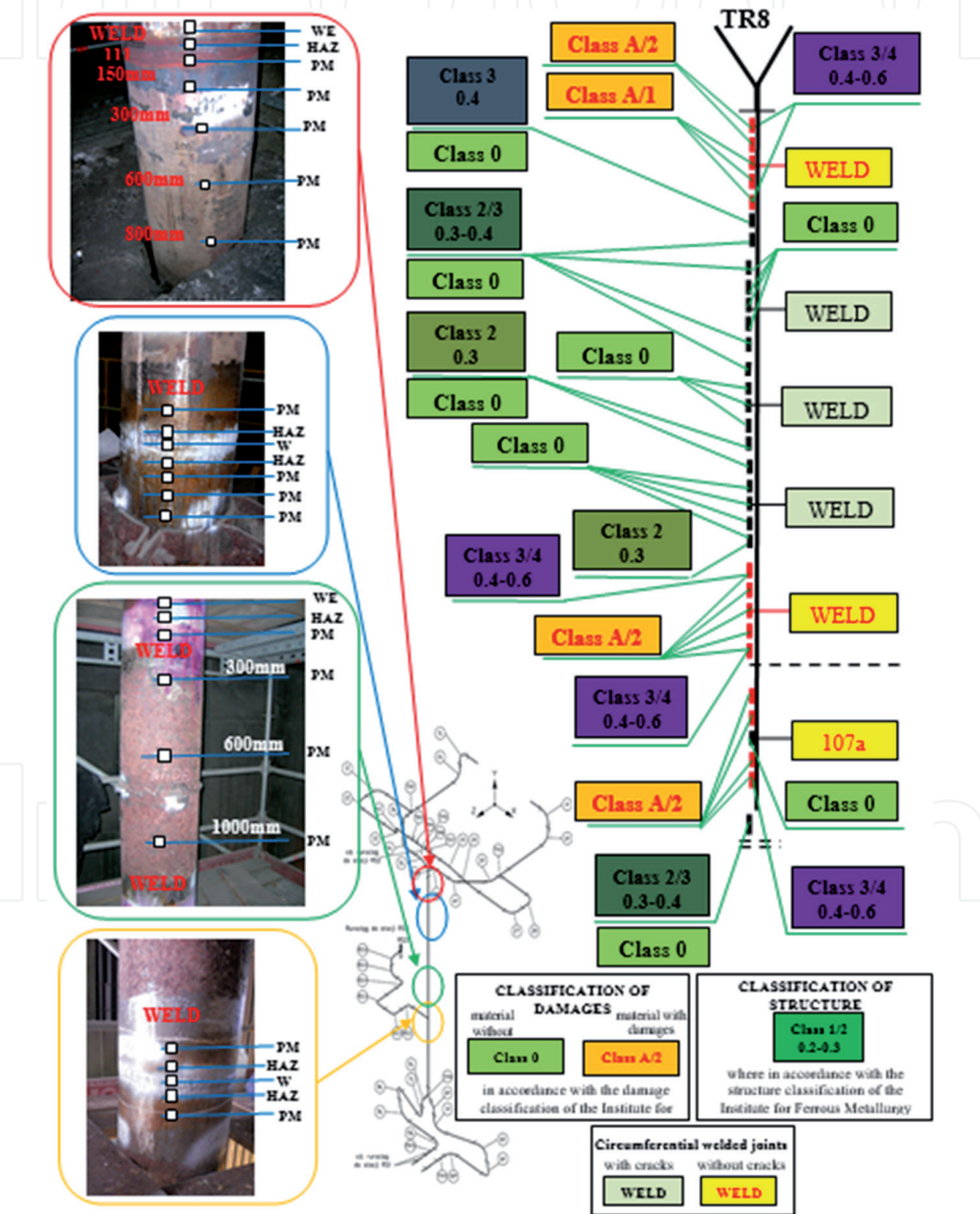


Figure 2. Assessment of the material condition with regard to changes in the structure and occurred internal damages caused by creep of parent material and circumferential welded joints in the vertical section of the primary steam pipeline made of 14MoV6-3 steel after approximately 220,000 h service (matrix replicas, SEM).

steam pipeline components after long-term service under creep conditions far beyond the design service time without internal damages caused by creep is shown in **Figure 1**, while those with disclosed damages in the form of voids both in the basic material and in the heat-affected zone and weld material are shown in **Figure 2**. The results of these tests allow to take decisions whether the test pipelines can be left and only some of its components need to be replaced using the joining technology by welding materials with significant changes in microstructure caused by creep with new materials.

The assessment of the exhaustion degree and the degree of internal damages in the material of welded joint components allows for determination of the residual and disposable life of the welded joint, capability of the materials of welded joint components to make a possible repair to the test joint, capability of the test basic materials to produce a repair (old/old material) or modernisation (old/new material) welded joint and propose the appropriate welding technology.

To ensure that the condition assessment of the material of welded joint components after long-term service under creep conditions by non-destructive methods is accurate and the estimated exhaustion degree is reliable, the results of destructive materials testing of these components are required. The results of these tests should allow the assignment of exhaustion degree to determined degrees of microstructural degradation of such joints.

The material for destructive materials testing is selected based on the results obtained by non-destructive method of matrix replicas, which determine the class of microstructure and the estimated exhaustion degree for parent material and the class of damage for butt components of welded joints. The material for destructive testing in the form of a test specimen of the component with butt-welded joint is taken from the areas with the highest exhaustion degree and adopted as representative for the component or installation.

3. Condition assessment of the material of welded joints operated beyond the design time using destructive methods

The destructive materials testing on long-time operated welded joints are carried out on homogeneous butt-welded joints of thick-walled components. Most often, these are welded joints of steam pipelines as well as steam superheater chambers and temperature controllers made of the following steel grades: 13CrMo4-5, 10CrMo9-10, 14MoV6-3, X20CrMoV121 and sometimes 15Mo3.

These tests include the observations of microstructure and hardness measurement of different areas of joints from parent material through heat-affected zone and weld. The simultaneous testing of mechanical properties and residual life of the welded joints and parent material are used to search for relations between the state of microstructure and these properties. It is also important to search for correlation between the mechanical properties, especially residual life, of the parent material and welded joint.

The characteristics created based on the obtained test results are used for assessing the condition and forecasting the further safe service of the parent material and welded joints operated beyond the design service time. Moreover, they are decisive in making decisions on the possibility of repairing welded joints using the materials after long-term service under creep conditions and developing the joining technologies.

3.1 Structure assessment of the material of welded joints operated for a long time under creep conditions

The selected example showing the state of structure of homogeneous butt-welded joints after long-term service compared to the structure of the parent material of a component after service far beyond the design service life is shown in **Figure 3** and summarised in **Table 1**.

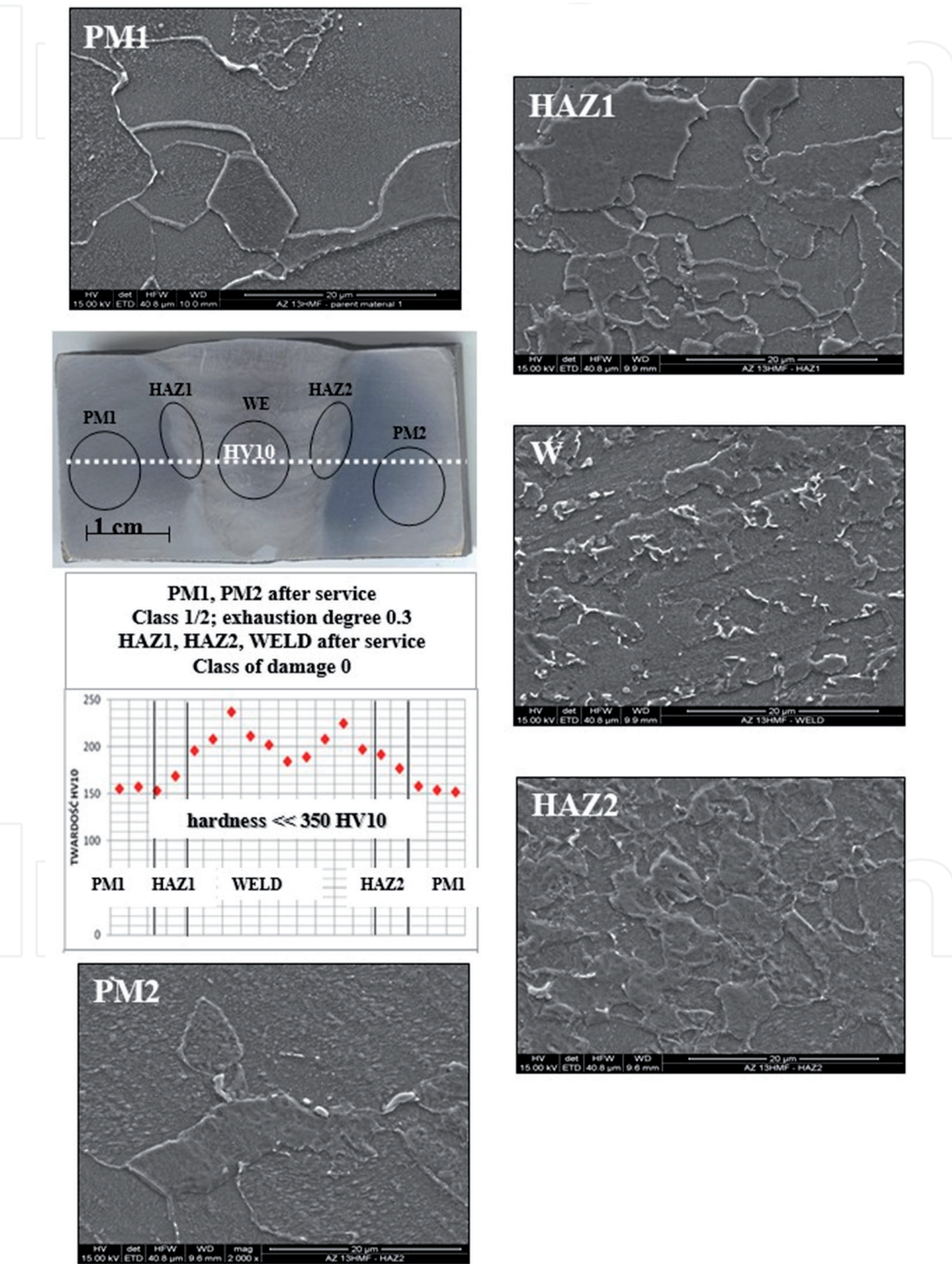


Figure 3. Structure of the material of homogeneous butt-welded joint components of the main primary steam pipeline made of 14MoV6-3 steel after approximately 200,000 h service under creep conditions parent material marked PM1, PM2; weld material marked WELD heat-affected zone marked HAZ1, HAZ2.

Figure 3 reveals the images of microstructure and the results of hardness measurements of components of the butt-welded joint in the main primary steam pipeline, whereas the description, state of microstructure of the parent material and its exhaustion degree as well as the class of internal damages of the heat-affected zones and weld for the selected example of welded joint are summarised in **Table 1**. The image of microstructure of the welded joint components after service, exceeding

Material used in testing		Description of microstructure	Hardness
Component	Test area	Material condition—exhaustion degree	HV10
Grade of material			
Service time			
Primary steam pipeline 14MoV6-3 (13HMF) 200,000 h	Parent material marked PM1	Ferritic-bainitic structure. Partially coagulated bainitic areas. Few precipitates of various sizes at the ferrite grain boundaries. Precipitates inside ferrite grains, mostly very fine, distributed evenly	156
	Parent material marked PM2	No discontinuities and micro-cracks are observed in the structure Bainitic areas: class I, precipitates: class a Damaging processes: class O Class 1/2, exhaustion degree: approximately 0.3	153
	Heat-affected zone marked HAZ1	Bainite with a small amount of ferrite. Significant number of fine precipitates in the bainitic areas and ferrite No discontinuities and micro-cracks are found in the structure	198
	Weld marked WELD	Bainitic areas of various sizes with a small number of ferrite. Bainitic areas with precipitates of various sizes No discontinuities and micro-cracks found in the structure	211
	Heat-affected zone marked HAZ2	Mixture of bainite and ferrite. Fine precipitates: in the bainite areas—distributed unevenly, in ferrite—distributed evenly. No discontinuities and micro-cracks found in the structure	181

Table 1.
State of microstructure, degree of exhaustion and hardness of the material of homogeneous butt joint components of test critical pressure components of power units after long-term service under creep conditions beyond the design service time, based on examples.

Standard	Chemical composition, %								
	C	Mn	Si	P	S	Cr	Mo	V	Ni
PN-75/H-84024	0.10	0.40	0.15	Max	Max	0.30	0.50	0.22	Max
Cr-Mo-V (13HMF)	0.18	0.70	0.35	0.040	0.040	0.60	0.65	0.35	0.30
Examined element MR1	0.16	0.61	0.33	0.020	0.020	0.48	0.51	0.31	0.08
Examined element MR 2	0.14	0.51	0.29	0.018	0.019	0.52	0.51	0.28	0.09

Table 2.
Analysis of chemical composition.

twice the value of the design service time, most often corresponds to the exhaustion degree which allows the material to be used in further service. It mainly results from significant difference between the design thickness and the actual thickness of the assessed components ($g_o < g_{act}$), which causes that the actual operating stress is lower than the design one ($\sigma_{act} < \sigma$), the as-received condition of the test materials and the correct previous service. Also, the frequent small differences in hardness level in the individual areas of the joints are a positive phenomenon affecting the suitability for further service.

Table 2 presents an analysis of the chemical composition of the tested sections. The mechanical properties of the material obtained from pipeline sections were shown in graphical form in **Figures 4–8**. In order to assess the properties of the tested steels and their welded joints, reference was made to the requirements contained in PN-75/H-84024.

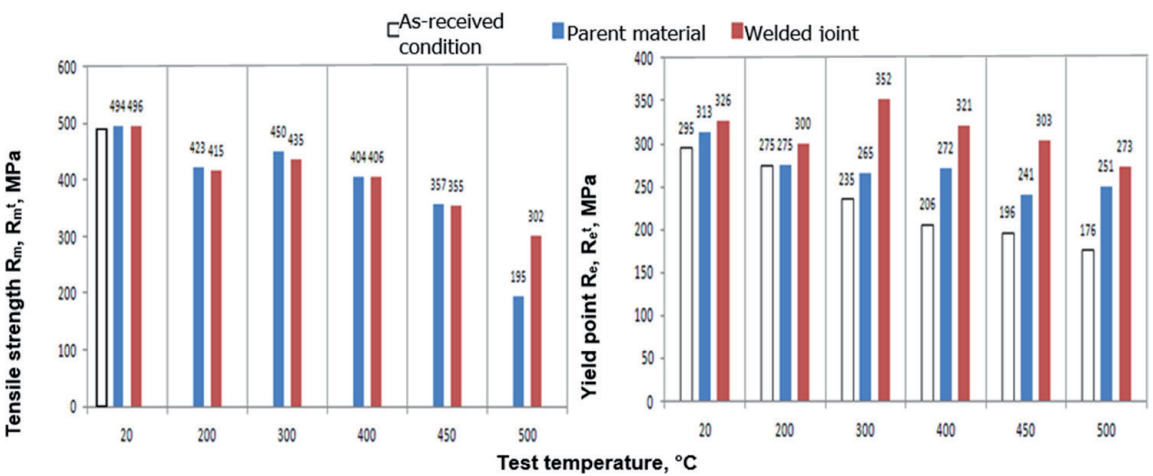


Figure 4.
The comparison of test results for yield point at room (R_e) and elevated (R_{eT}) temperature of the parent material and butt-welded joint of the primary steam pipeline made of 14MoV6-3 steel after 240,000 h service under creep conditions in relation to the as-received condition of the material.

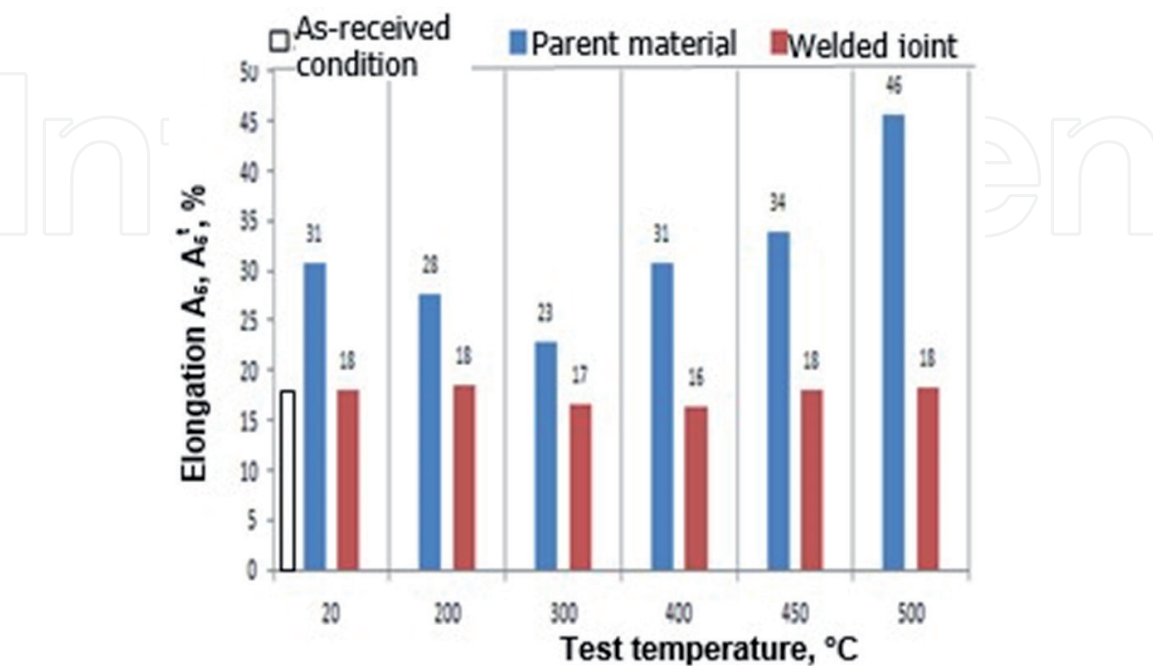


Figure 5.
The comparison of test results for A_{sT} elongation at room and elevated temperature of the shell material and butt-welded joint of the primary steam pipeline made of 14MoV6-3 steel after 240,000 h service.

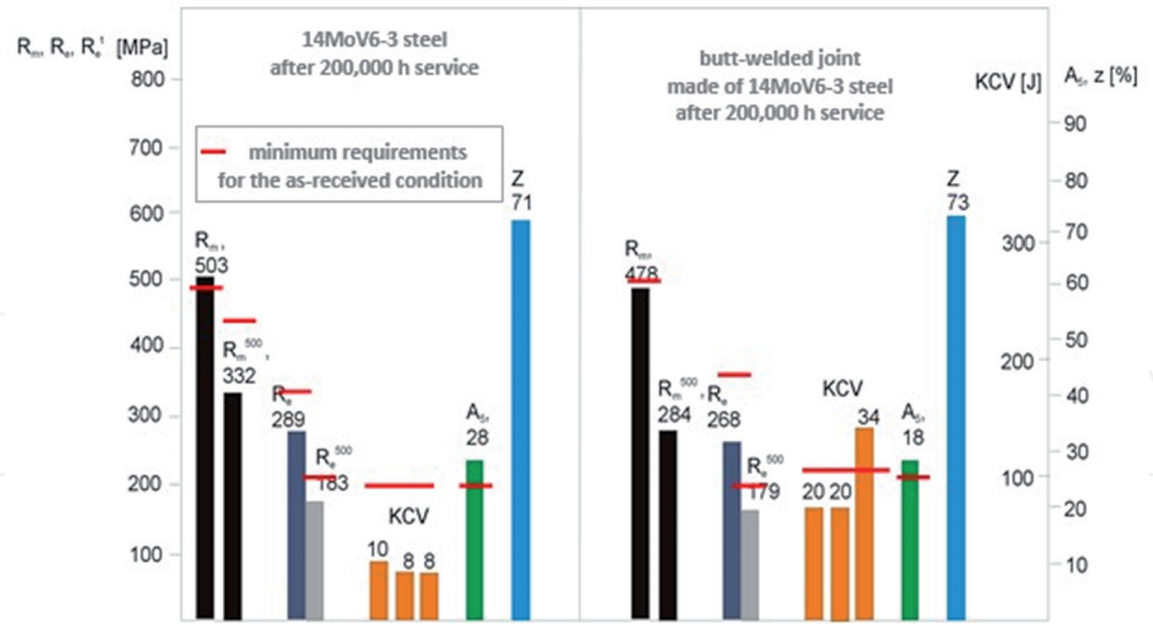


Figure 6. The comparison of test results for mechanical properties of the parent material and homogeneous butt-welded joint of pipeline components made of 14MoV6-3 after long-term service under creep conditions for 200,000 h.

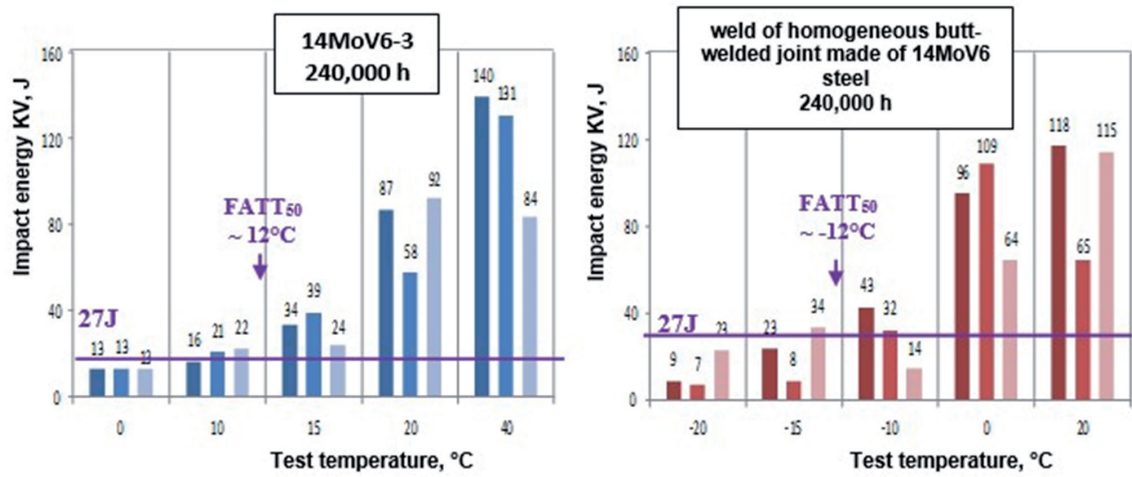


Figure 7. The comparison of test results for impact energy measured on V-notch test specimens depending on test temperature of parent material and weld of homogeneous butt-welded joint of pipeline components after long-term service under creep conditions: (a) made of 14MoV6-3 steel, (b) made of 10CrMo9-10 steel.

3.2 Assessment of mechanical properties of the material of welded joints operated for a long time under creep conditions

Another element of the materials characteristics is the mechanical properties of welded joints after service and their level. Most often, the level of tensile strength and yield point at room temperature and of tensile strength at elevated temperature of such welded joints after service, for a time much longer than the design time, corresponds to the required minimum values for the parent material in the as-received condition, or their actual values are not much lower. The example of such characteristics is shown in **Figure 4**. The level of these properties is very important for the determination of the rate of start-ups and shutdowns, which is connected with the level of instantaneous internal stresses resulting from the temperature gradient, particularly of thick-walled components. It is also important to know the formability of the material of welded joints, which can be reflected by the

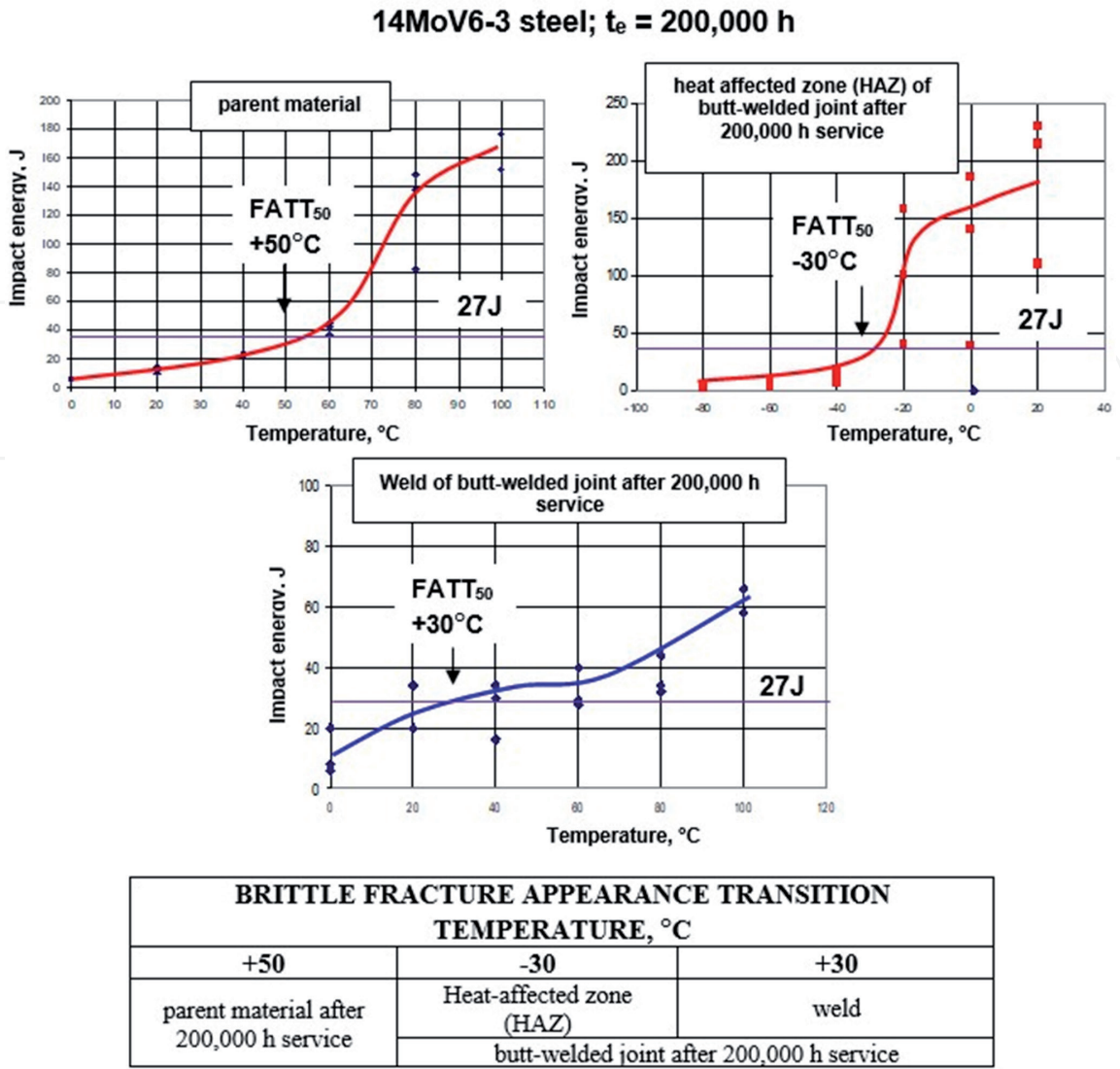


Figure 8.
The relationship between the impact energy measured on V-notch test specimens and the test temperature of butt-welded joint components of steam pipeline made of 14MoV6-3 steel after 200,000 h service and the brittle fracture appearance transition temperature determined for (a) parent material, (b) heat-affected zone and (c) weld.

elongation in tensile test, its impact energy and brittle fracture appearance transition temperature both in the weld and the heat-affected zones. The example of elongation test results depending on the test temperature of welded joints compared to the parent material after long-term service far beyond the design service time is shown in **Figure 5**, whereas **Figure 8** presents the comparison of mechanical properties of the parent material and butt-welded joint with regard to the requirements for the parent material in the as-received condition.

The test results for impact energy measured on V-notch test specimens depending on the test temperature of parent material and weld of homogeneous butt-welded joint of the pipeline components after long-term service under creep conditions are compared in **Figure 7**, whereas **Figure 8** shows the relationship between the impact energy measured on V-notch test specimens and the test temperature of the parent material, heat-affected zone and weld of the butt-welded joint of the main steam pipeline made of 14MoV6-3 steel after 20,000 h service as well as brittle fracture appearance transition temperatures determined for the materials of these areas. This example illustrates how diversified the level of brittle fracture appearance transition temperature of the material of individual welded joint components after long-term service under creep conditions can be.

In accordance with the results of long-term own research, for the materials that most often exist in the components operated under creep conditions far beyond the design service time, such as 13CrMo4-5, 14MoV6-3, 10CrMo9-10 low-alloy steels and X20CrMoV121 high-chromium steel, the highest trend towards the loss of plastic properties is shown by the components made of 14MoV6-3 steel and then those made of X20CrMoV121 steel. The knowledge of these material features is necessary for the selection of water-pressure test parameters and the method for overhaul works and repairs.

It should be noted that for components in long-term use, the leak water tests can only be carried out. The use of strength water test may result in destruction of the component being operated. Such a test can only be carried out for the new equipment, and the governing standards apply to new equipment only.

It can be concluded that with an increase in the exhaustion degree, the mechanical properties of the material being operated are reduced. However, no unambiguous relationships between the level of properties, both strength and plastic, and the residual life and exhaustion degree caused by creep were observed so far. According to the present knowledge, such a correlation does not exist.

3.3 Assessment of residual life and disposable residual life of the material of welded joints operated for a long time under creep conditions

The most critical element of the materials characteristics is the creep resistance level of the welded joints being operated. This creep resistance is responsible for

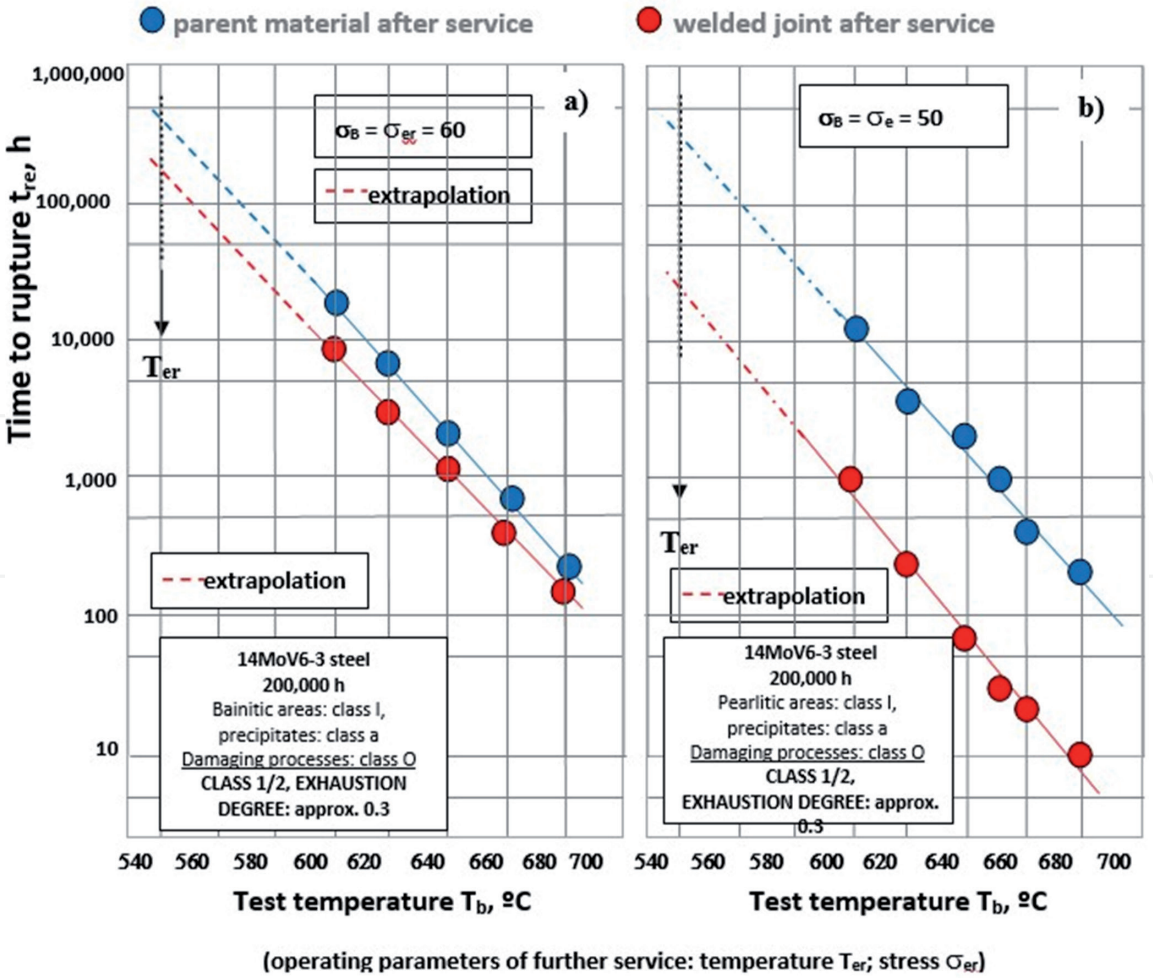


Figure 9. Residual life of parent material and butt-welded joints of components working far beyond the design service time based on results of short-term creep tests in the form of $\log t_{re} = f(t_b)$ at $\sigma_b = \text{const}$ for two different main primary steam pipelines made of 14MoV6-3 steel after 200,000 h service. σ_B - test stress.

Steel grade	Test area	Material used in testing		Adopted operating parameters of further service		Determined residual life, h	Estimated disposable residual life, h
		Type of component Service time	Dimensions of $D_{out} \times g_n$, mm	Stress σ_D , MPa	temperature T_D , °C		
14MoV6-3	Parent material	Primary steam	$\phi 327 \times 40$	60	540	300,000	165,000
	Welded joint	pipeline 200,000 h				200,000	110,000
14MoV6-3	Parent material	Primary steam	$\phi 327 \times 40$	50	540	140,000	77,000
	Welded joint	pipeline 200,000 h				35,000	19,000

Table 3.
Residual life and disposable residual life based on the results of short-term creep tests on the materials of the main primary steam pipelines made of 14MoV6-3 steel after long-term service far beyond the design service time.

their ability to transfer the actual service loads of the component, which occur under operating conditions. A measure of creep resistance is the level of residual creep resistance, which is able to meet these expectations. However, in the engineering practice, the safe service of the welded joints operated under the preset temperature and pressure conditions is important. The time of safe service is the disposable residual life, which is part of the residual life being determined.

The examples of residual life, which is the time to rupture under the temperature and stress conditions equal to operating ones, determined in short-term creep tests and compared to the residual life of the parent material after service are shown in **Figure 9**.

The determined residual life and disposal residual life for the presented examples are summarised in **Table 3**. The comparison of the residual life and disposable residual life determined for the material of two primary steam pipelines made of 14MoV6-3 steel after 200,000 h service shows significant differences. These differences probably result mainly from differences in the as-received condition of the operated material and welded joint as well as different service history. This confirms the need of an individual assessment, mainly based on the assessment of the actual condition of the component and its material.

4. Summary

Based on many power units in use, the results of creep tests on the butt-welded joints after long-term service beyond the design time carried out on the parent material and butt-welded joints of the components operating under creep conditions invalidate the generally accepted principle that the residual creep strength of the material of welded joint is no less than 80% the residual creep strength of the basic material. The principle of the relationship of residual creep strength between them transferred from that applicable to the basic material and welded joint in the as-received condition is not supported by the investigations of real cases. Also, in many investigated cases, the residual life of the welded joint is significantly lower than that obtained for the parent material. Therefore, for the components and materials operated far beyond the design time, it is necessary to determine the residual life not only for the basic material of the representative test specimen of the component but also for the welded joint (**Table 3**).

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