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THE SERVICE LIFE OF THE REPAIR WELDED JOINT OF Cr-Mo / Cr-Mo-V

This paper presents the evaluation of the service life of dissimilar repair welded joint from Cr-Mo/Cr-Mo-V steel after 200,000 h service under creep condition. The investigations of microstructure using scanning electron microscopy, investigations of mechanical properties at room and elevated temperature as well as creep tests of the basic material from Cr-Mo and Cr-Mo-V steel and welded joint from these steels were carried out. The investigations allowed the time of further safe operation of the repair welded joint in relation to the residual life of the materials to be determined. The evaluation of residual life and disposable residual life, and thus the estimation or determination of possible time of further safe operation, is crucial when the elements are operated much beyond the design work time.

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

1. Introduction

At present, the time of operation of the majority of Polish power stations and heat and power generating plants, frequently beyond 200,000 h, results in aiming the main efforts to maintain the level of electric energy production in Poland at the extension of operation much beyond the design work time with simultaneous modernisation of boilers and turbines in order to improve their technical and economic indicators (by increasing the power and improving the efficiency and availability), extend their service life, and, above all, reduce the emission of harmful pollutants to the atmosphere, water and soil [1-4].

Such an unplanned operation of power boilers in Poland extended beyond 200 000 h requires a new approach to development of procedures for diagnosing these materials. A particularly important problem for a failure-free operation is the strength of welded joints of steam pipeline elements working under creep conditions [5-10].

For determination of the time of safe operation for material of the pipelines working under creep conditions, particularly after exceeding the design work time, the knowledge of their residual creep strength is necessary.

In most diagnostic works, the investigations on welded joints of steam pipelines are based on non-destructive magnetic particle testing the purpose of which is to reveal the existence of micro-cracks, and to a much less extent on microstructure investigations by light microscopy. It should be emphasised here that the magnetic particle testing is one of the elements of non-destructive inspection of welded joints and they do not give information on the state and degree of material degradation [11-14]. And the observation of microstructure by light microscope can only be used to assess the correct preparation of metallographic microsection. To properly evaluate the material condition, i.e. the exhaustion degree, based on changes in the microstructure of the analysed material, the examinations should be made by scanning electron microscopy with magnifications of up to 5 000x and suitable resolution of microstructure images. The evaluation of exhaustion degree of the examined materials based on non-destructive testing requires a database including the material characteristics of changes in the level of mechanical properties and residual creep strength with regard to the condition of microstructure [15-18]. It concerns not only the diagnostics of welded joints after long-term service, but above all the assessment of behaviour of the material and repair welded joints in the as-received condition with material after long-term service [19-23].

2. Material for investigations

The material for investigations included two specimens of the primary and secondary steam pipeline after 200,000 h service under creep conditions, i.e. at 540°C and steam pressure of 3 and 14MPa for the primary and secondary steam, respectively. The “repair” welded joint was made on the acquired specimen under industrial conditions to simulate the steam pipeline repairs made by welding.

Test joints were made according to PN-EN ISO 4063: 2009. The welding filler metals were selected on the basis of chemical composition of the basic materials being welded and by analysing their characteristic transformation temperatures Ac1. The transformation temperatures are also connected with selection of soaking heat during heat treatment after welding. For welding of pipe sections made of two different materials,

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the welding filler metals were selected as for 13HMF steel. Before welding, the pipe sections were heated up to a temperature of 200 – 250°C in the area of edges prepared for welding. The inter-pass temperature was controlled too and it did not exceed 300°C. Immediately after welding, the joint was subject to heat treatment:

- heating up to tempering (annealing) temperature v = max 120°C/hour,
- soaking heat: 720°C,
- soaking time: 3 hours,
- cooling after soaking – with furnace to 300°C at a rate of v = max 100°C/hour, and then with air.

After welding and heat treatment, the welded joint was subject to non-destructive testing, which completed successfully.

3. Methodology of investigations

The mechanical property testing included static tensile test at room and elevated temperature with the testing machine Zwick with max load of 200 kN, Vickers hardness measurement with Future – Tech FM – 7 hardness testing machine by using the indenter load of 10 kG, and impact test on standard V-notched test samples. The microstructure investigations were carried out with the scanning electron microscope (SEM) Inspect F on metallographic microsections prepared in a conventional manner. The abridged creep tests at the temperature above the operating one and at the stress similar to the operating one were carried out with single-sample machines Instron at the temperature accuracy during the test of ±1°C.

4. Results of investigations

The chemical composition of the material of examined primary and secondary steam pipeline specimens in relation to the standard specification requirements is provided in Table 1 [24]. The results of check analysis of chemical composition revealed that the material of the examined specimens taken from critical elements in pressure sections of the power unit after long-term service under creep conditions were in conformity with requirements of the standard for chemical composition of the examined steels.

Hardness measurements of the repair circumferential welded joint from Cr-Mo/Cr-Mo-V steel were carried out on transverse metallographic specimen, which is shown in Fig. 1.

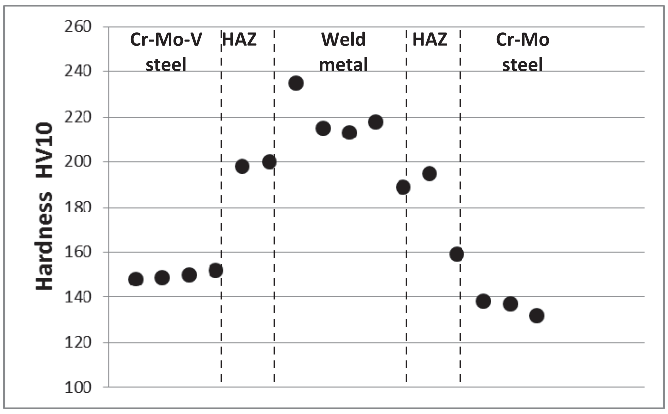

Fig. 1. Results of hardness measurements of dissimilar circumferential repair welded joint (Cr-Mo-V/Cr-Mo)

The hardness measurement through individual zones of the joint revealed no sudden changes. The maximum difference in hardness from Cr-Mo steel parent material through HAZ, weld, HAZ to Cr-Mo-V steel parent material is approx. 110 units and does not exceed the maximum acceptable value of 350 HV10.

The microstructure investigations on metallographic microsections were performed using scanning electron microscope with magnifications of 500, 1000, 2000 and 5000x. The results of investigations in the form of microstructure images of the repair circumferential welded joint are presented in Fig. 2. The description of microstructure including the assessment and estimated exhaustion degree of the welded joint was made based on the classification of the Institute for Ferrous Metallurgy (Table 2).

The microstructure degradation in Cr-Mo and Cr-Mo-V steel was described as a set of microtructural and physicochemical factors that are changed under elevated temperature and stress over a relatively long time. The general steel microstructure instability criteria include: extent of changes in microstructure, carbide transformations, changes in morphology of phases (distribution, shape, size and distance between particles); extent of disintegration of pearlite/bainite areas, degree of matrix depletion of the alloying elements. The above-mentioned factors have a significant impact on mechanical properties of the examined steels [1].

The methodology for evaluation of the condition of examined steels after service under creep conditions based on the assessment of changes in the microstructure of constituent processes, i.e.: changes in pearlite/bainite microstructure, changes in development of precipitation processes and changes

TABLE 1

Analysis of chemical composition

Standard	Chemical composition, %								
	C	Mn	Si	P	S	Cr	Mo	V	Ni
PN-75/H- 84024 Cr-Mo-V (13HMF)	0.10 0.18	0.40 0.70	0.15 0.35	max 0.040	max 0.040	0.30 0.60	0.50 0.65	0.22 0.35	max 0.30
Examined element	0.15	0.47	0.31	0.021	0.018	0.49	0.54	0.34	0.08
PN-75/H- 84024 Cr-Mo (10H2M)	0.08 0.15	0.40 0.60	0.15 0.50	max 0.030	max 0.030	2.0 2.5	0.90 1.10	-	max 0.30
Examined element	0.12	0.47	0.42	0.020	0.019	2.04	0.97	-	0.09

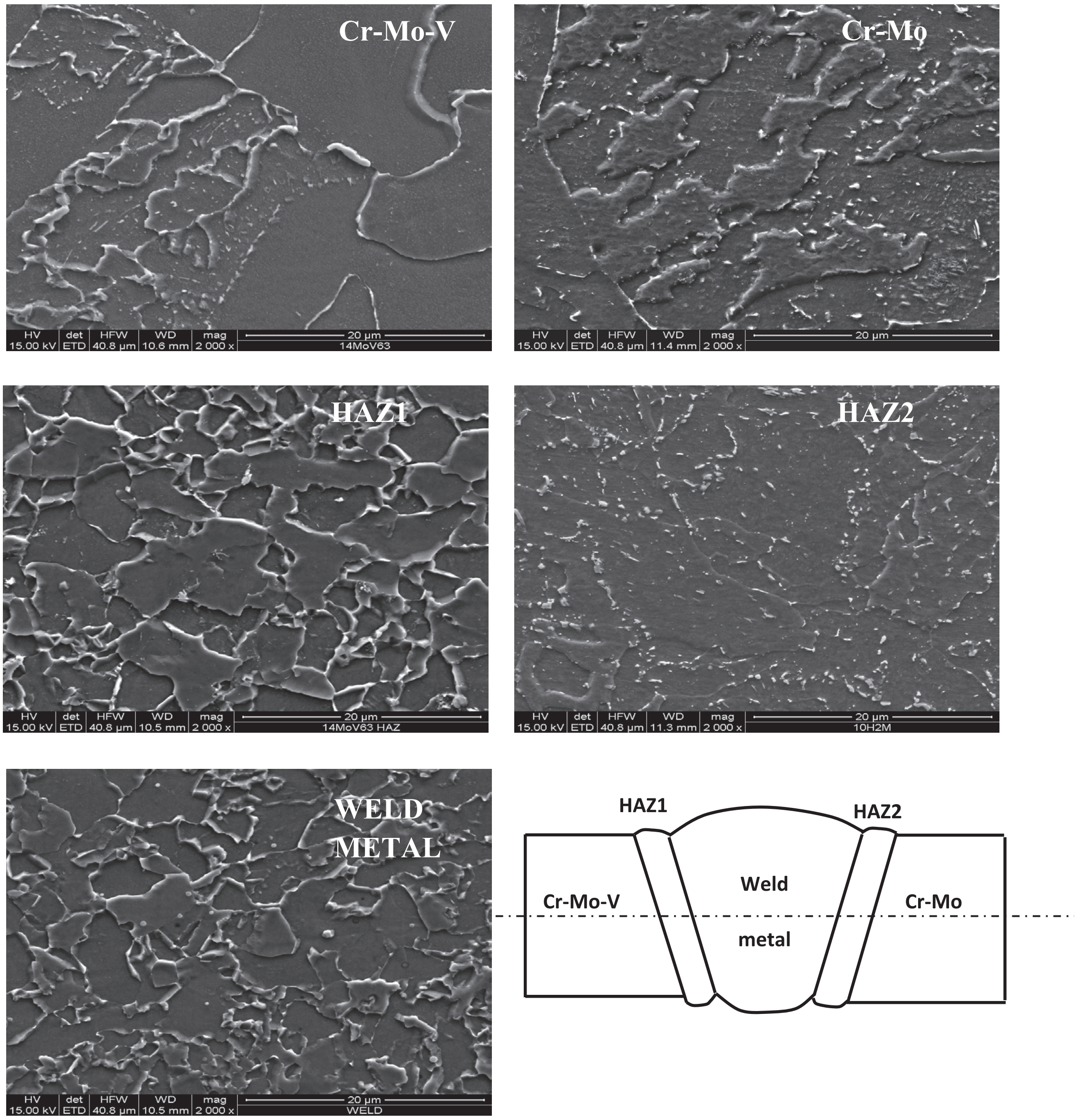

Fig. 2. Microstructure of the material of repair welded joint elements

TABLE 2

Evaluation of the results of microstructure investigations of dissimilar repair welded joint elements

Test area	**Description of microstructure** **Material condition – exhaustion degree**
Parent material 13HMF steel	Ferritic-bainitic microstructure. Partially coagulated bainitic areas. Precipitations of different size at the ferrite grain boundaries. Inside the ferrite grains, there are very fine evenly distributed precipitates. No discontinuities and micro-cracks are observed in the microstructure. No initiation of damaging processes is observed. Bainitic areas: class I, precipitates: class a Damaging processes: class O **CLASS 1/2, EXHAUSTION DEGREE: approx. 0.3**
Parent material 10H2M steel	Ferritic-bainitic microstructure. Partially coagulated bainitic areas. Fine precipitations at the ferrite grain boundaries. Mostly very fine precipitations inside ferrite grains. No discontinuities and micro-cracks are observed in the microstructure. No initiation of damaging processes is observed. Bainitic areas: class I, precipitates: class a Damaging processes: class O **CLASS 1/2, EXHAUSTION DEGREE: approx. 0.3**
Heat-affected zone, weld – repair joint	Heat-affected zone microstructure. No discontinuities and micro-cracking are found in the microstructure.

TABLE 3

Results of investigations of strength properties

Designation	Strength properties			
	Rm	Re	A	Re^{500}
	MPa	MPa	%	MPa
Parent material 13HMF	535	326 $^{1)}$	24	221
repair joint 10H2M + 13HMF	479	218 $^{1)}$	23	190
Parent material 10H2M	482	229 $^{1)}$	27	193
REQUIREMENTS FOR 13HMF STEEL IN THE AS-RECEIVED CONDITION TO PN-75/B-84024	**490÷690**	**min 365**	**min 18**	**min 216**
REQUIREMENTS FOR 10H2M STEEL IN THE AS-RECEIVED CONDITION TO PN-75/B-84024	**440÷590**	**min 265**	**min 20**	**min 186**

does not meet the requirements of PN-75/H-84024

in development of internal damages related to the exhaustion degree, are presented in [1].

The evaluation of the above-mentioned constituent elements of microstructure and the assigned corresponding classes revealed based on the microstructural investigations allowed the main class of the microstructure and the corresponding exhaustion degree to be determined.

The investigations of strength properties of the Cr-Mo and Cr-Mo-V steels and the repair joint were carried out in tensile test at room temperature and at a temperature similar to the working temperature (500°C) to determine the tensile strength R_m, yield point R_e, elongation A, and reduction of area Z. The investigation results are provided in Table 3.

For the Cr-Mo and Cr-Mo-V steels after more than 200,000 h service and the repair welded joint the obtained tensile strength at room temperature and yield point at a temperature similar to the operating one were higher than the minimum ones required for this steel in the as-received condition pursuant to PN-75/H-84024, whereas the obtained values of yield point at 500°C for all the tested conditions, i.e. Cr-Mo and Cr-Mo-V steels and welded joint, are lower than the minimum ones required for the examined steel in the as-received condition.

The value of impact strength and brittle fracture appearance transition temperature depends on the condition of microstructure and corresponding exhaustion degree of the examined material. With increase in the degree of degradation, the brittle fracture appearance transition temperature moves towards the higher values. This trend is much more distinct for the long-term service of the Cr-Mo-V steel than of the Cr-Mo one. The brittle fracture appearance transition temperature determined for the examined conditions is +50°C for Cr-Mo-V, -20°C for Cr-Mo and +20°C for the weld material (Fig. 3).

For the elements from materials that do not meet the requirements for brittleness threshold of 27J at room temperature and strength properties, the appropriately modified procedure for conducting water pressure tests should be used and the necessity of possibly modifying the boiler start-up and shut-down procedure should be considered. This will allow to avoid possible unexpected breakdowns due to the lack of ability to transfer the required excessive loads [25,26].

To reduce the duration of creep tests and residual life evaluation, the abridged creep tests with duration of a few dozen to max 10,000 h were applied. This makes it possible to obtain test results within maximum several months, yielding good estimation of residual life, which was verified in [27,28]. The acceleration of the creep process and reduction in duration of testing is obtained in creep tests, which are carried out with uniaxial tension on test pieces sampled from the examined material. The tests are made with constant test stress corresponding to the operating stress and at different test temperature levels, much higher than the operating temperature.

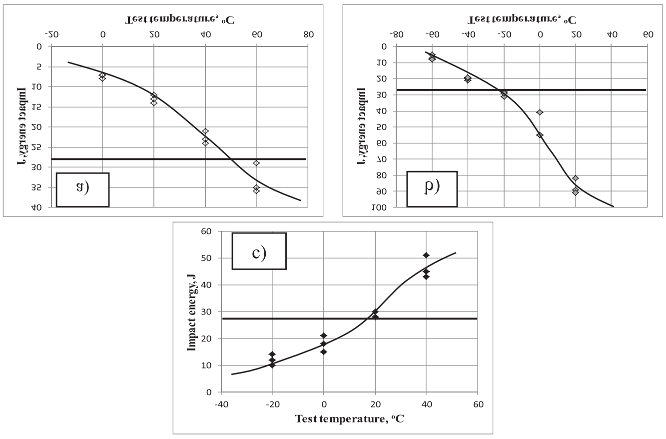

Fig. 3. Brittle fracture appearance transition temperature determined for: a) Cr-Mo-V steel, b) Cr-Mo steel, c) repair weld material.

The abridged creep tests were conducted at constant test stress corresponding to the operating stress $\sigma_b = \sigma_r$ =const and at constant test temperature T_b for each of the tests, yet with different values from 600ºC to 680ºC in 20ºC increments. The results of the tests are presented as a relationship log t_r =f(Tb) at σb = const, where t_r means the time to rupture in creep test. They allow drawing the straight line inclined towards the axis of the time to rupture t_r. The residual life is determined by extrapolating the obtained straight line towards the lower temperature corresponding to the operating one T_e.

The abridged creep tests of the Cr-Mo and Cr-Mo-V steels and the welded joint were carried out at the constant stress level σ_b=55 MPa, corresponding to the assumed working stress σr of further service. The test results are presented as the relationship log tr = f(T_b) at $\sigma_b \approx \sigma_r$ in Fig. 4.

The residual life determined based on abridged creep tests are summarised in column 2 of Table 4, whereas the disposable residual life of the examined elements estimated on this basis for the adopted parameters of further service Tr = 540°C and sr = 55 MPa is summarised in Table 4, column 3, and it represents the forecast of the remained time of further safe operation.

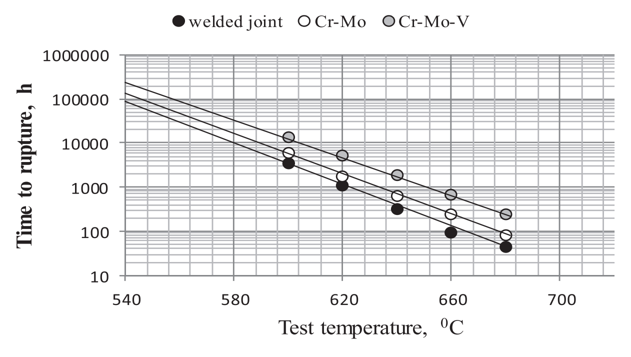

Fig. 4. Characteristics of temporary creep strength for Cr-Mo and Cr-Mo-V steels and repair welded joint after more than 200,000 h service

TABLE 4

Forecast service life of Cr-Mo and Cr-Mo-V steels and circumferential welded joint based on abridged creep tests

Designation	Residual life at 540°C	Disposable residual life at 540°C
1	2	3
Cr-Mo-V	220,000 h	120,000 h
Cr-Mo	120,000 h	66,000 h
Repair joint	90,000 h	50,000 h

5. Conclusions

- The microstructure investigations of the Cr-Mo and Cr-Mo-V steels after more than 200,000 h service under creep conditions allowed them to be assigned the exhaustion degree of 0.3 according to the Institute for Ferrous Metallurgy's classification.
- For any of the examined conditions, i.e. the parent material of Cr-Mo and Cr-Mo-V steels and the repair welded joint, the obtained yield point values at the temperature of 500°C similar to the operating temperature are below the minimum ones required for the examined steels in the as-received condition. For the elements from materials that do not meet these yield point requirements and the impact strength criterion of 27J at room temperature, the appropriately modified procedure for conducting water pressure tests and the procedure for starting up and shutting down the boiler should be used.
- The creep resistance tests of the Cr-Mo and Cr-Mo-V steels and the repair welded joint revealed that the Cr-Mo-V steel was characterised by the highest disposable residual life (120,000 h), whereas the service life of the repair welded joint (50,000 h) was by 25% lower than the disposable residual life of the Cr-Mo steel (66,000 h).
- It was demonstrated that, opposite to the microstructural investigations and the basic investigations of mechanical properties, the abridged creep tests allowed the real determination of the time of further safe operation of power equipment elements working beyond the design service life.
- The procedure for evaluation of the quality of repair welded joints presented in the paper is continued by its authors for different exhaustion degrees of the 13HMF, 10H2M and 15HM steels to determine the effect of the material condition on the service life of repair welded joints.

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