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Structure of welded joints of 14MoV6-3 and 13CrMo4-5 steel elements after design work time under creep conditions

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ABSTRACT

Purpose: This paper is to present changes in the structure of material of 14MoV6-3 and 13CrMo4-5 alloyed steel components of power station boiler after long-term creep service.

Design/methodology/approach: The investigated materials were obtained from Polish power stations. All the examined elements have exceeded their assessed life of 100 000 hours. The structural investigations were carried out on materials after long-term service under creep conditions. The microstructure was observed using light and scanning electron microscope. The investigations on the development of precipitation processes were done by X-ray diffraction phase analysis.

Findings: Carbide precipitation evolution in correlation to the life exhaustion extent was presented.

Practical implications: The presented methods can be used for evaluation of materials working under creep conditions.

Originality/value: The presented results on changes in the structure and precipitation processes are applied to evaluation of the condition of elements in further industrial service.

Keywords: Structure; Welded joint; Steel 14MoV6-3; 13CrMo4-5

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MATERIALS

1. Introduction

In the domestic power industry, not many newly erected units have been reported for the last several years. It has made the electric energy manufacturers direct their main efforts at maintaining the existing units available and at the same time ensuring their safe operation [1-8]. In addition, most of the power units operating in Poland exceeded their design time of safe service in the 1980s, and their number has been increasing year after year. That caused that the issue of extending their service time beyond the design one has acquired particular importance [9-16]. Thus, the proper method for maintaining the availability of the units has become to carry out inspections and repairs with simultaneous rational diagnostics.

The first and necessary stage of modernisation is to archive the unit's condition, which involves the diagnostic testing aimed at technical evaluation of the pressure part of boiler and turbine. One of the main elements of this evaluation is the condition assessment of the material of elements. It mainly concerns the critical elements, i.e. those working under the most difficult temperature and stress conditions and above the limit temperature, that is under creep conditions [17-23].

The condition assessment system developed by the Institute for Ferrous Metallurgy for materials after long-term service requires, among other things, the evaluation of changes in structure. The evaluation of these changes can be made based on the image of microstructure with regard to changes in its phase components, development of internal damages and development of precipitation processes as well as morphological features of carbides based on their size and distribution of types. This way of material condition assessment without the need of destructive testing is allowed by the method of matrix replicas that reflect the image of structure, which the method is successfully used in diagnostics of the pressure parts of boilers [6,9,14].

To evaluate the material condition by non-destructive methods, it is necessary to have a database in the form of materials characteristics including the strength and plastic properties and changes in structure, but first of all the characteristics of creep strength for materials with different grades of degradation due to service under creep conditions [11,13,14].

The basic source of information for verification and expansion of the database on materials for the power industry is the results of destructive testing conducted on elements after service, which is the subject of this study.

2. Material for investigations

The material for investigations was 13CrMo4-5 and 14MoV63 low-alloy steel homogeneous circumferential welded joints of elements of the pressure part of boiler after long-term service under creep conditions the duration of which has significantly exceeded the assumed time. The following test pieces were acquired for investigations:

- 14MoV6-3 (13HMF) steel primary steam pipeline after 200.000 h service at 540°C and pressure of 14.3 MPa, with dimensions of ϕ327x40mm (Fig. 1);
- 13CrMo4-5 (15HM) steel II° secondary steam header after 140.000 h service at 490°C and pressure of 6.0 MPa, with dimensions of ϕ410x20mm (Fig. 2).

Chemical composition of steels tested with regard to the requirements of standard is presented in Table 1.

Fig. 1. Material for investigations in the form of 14MoV6-3 (13HMF) steel homogeneous circumferential welded joint of primary steam pipeline after 200,000 h service

3. Range of testing

As a part of the tests, the properties of the material of welded joints were evaluated. The following was subject to testing in the material condition assessment and evaluation of the required utility properties of welded joints:

- structure of circumferential welded joints of the elements of pressure part of boiler after long-term service;
- phase composition of carbide precipitations;
- hardness of individual elements of joints and its nature from parent material through heat-affected zone and weld.

The obtained test results will be the verification of proposed method for assessment and prediction about the time of further safe service of Cr-Mo and Cr-Mo-V steel homogeneous circumferential welded joints. In case of the positive result, the test method will be used in materials diagnostics performed as a part of direct orders from the industry.

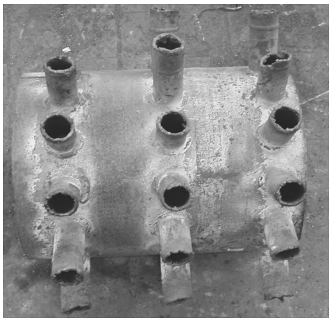


Fig. 2. Material for investigations in the form of 13CrMo4-5 (15HM) steel homogeneous circumferential welded joint of II° secondary steam superheater header shell after 140,000 h service

4. Microstructural investigations

The structure of 13CrMo4-5 steel in initial state is the mixture of ferrite and pearlite, while in pearlite areas colonies occur where cementite lamellas are parallel to one another. Within a single pearlite area, these colonies are arranged at different angles in relation to one another. The example of characteristic structure of 13CrMo4-5 steel in initial state is shown in Fig. 3.

In turn, the structure of 14MoV6-3 steel in initial state is the mixture of bainite and ferrite, sometimes with slight content of pearlite. In addition, very fine precipitations of MC carbides inside ferrite grains are observed within the structure, while in the bainite areas there are small spheroidal cementite precipitations and in the pearlite colonies - cementite lamellas. The example of characteristic structure of 14MoV6-3 steel in initial state is shown in Fig. 4.

4.1. Evaluation of microstructure and hardness after long-term service

The microstructural investigations were performed on metallographic microsections (Figs. 5, 6). The microsections made on cross-section of test pieces of the examined elements in weld area were prepared by grinding and polishing followed by etching.

The observations were carried out with Philips XL30 scanning electron microscope at magnifications from 200 to 5000×. The areas of microstructural observation of the material of inlet header and the material of primary steam pipeline are shown in Fig. 7.

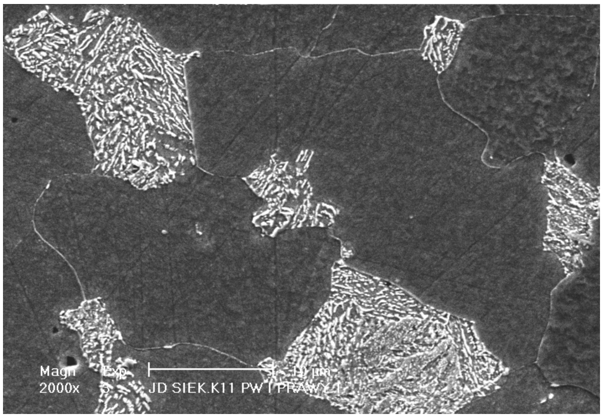
The test results in the form of structure images of the materials of inlet header circumferential welded joint and primary steam pipeline elements, in particular: parent material, heat-affected zone of joint and weld, are shown in Figs. 8 and 9.

The structure description with assessment and estimated exhaustion extent te/tr based on the own classification of the Institute for Ferrous Metallurgy is provided in Tables 2, 3.

Table 1.
Chemical composition of the material of tested elements

Grade	Chemical composition [%]					
	C	Mn	Si	Cr	Ni	Mo
14MoV63	0.12	0.51	0.25	0.35	0.051	0.52
Wg PN-EN 10216-2	0.08 0.14	0.30 0.70	max 0.50	2.00 2.80	max 0.30	0.90 1.10
13CrMo4-5	0.15	0.58	0.23	0.89	0.096	0.43
Wg PN-EN 10216-2	0.10 0.17	0.40 0.70	max 0.35	0.70 1.15	max 0.30	0.40 0.60

a)



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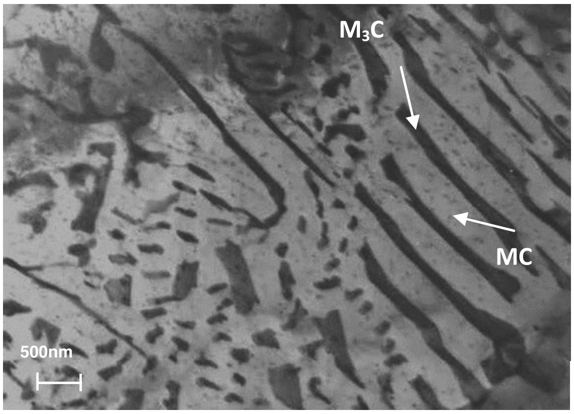
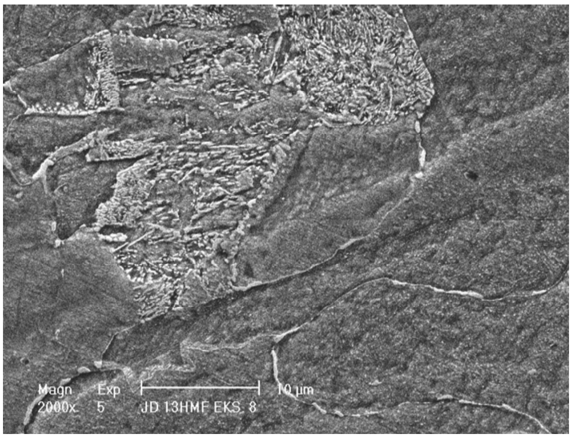


Fig. 3. Ferritic-pearlitic structure of 13CrMo4-5 steel in initial state a) SEM, b) TEM

a)



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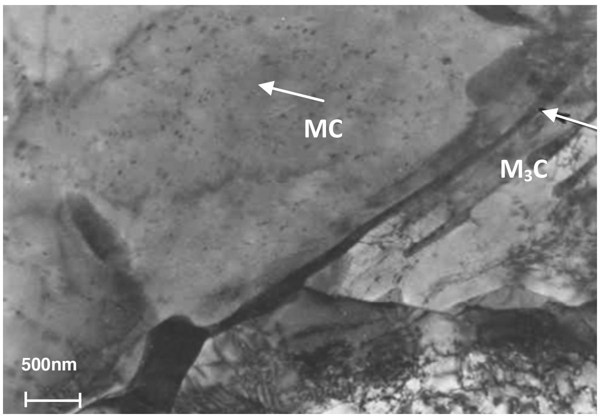

Fig. 4. Ferritic-bainitic structure of 14MoV6-3 steel in initial state a) SEM, b) TEM

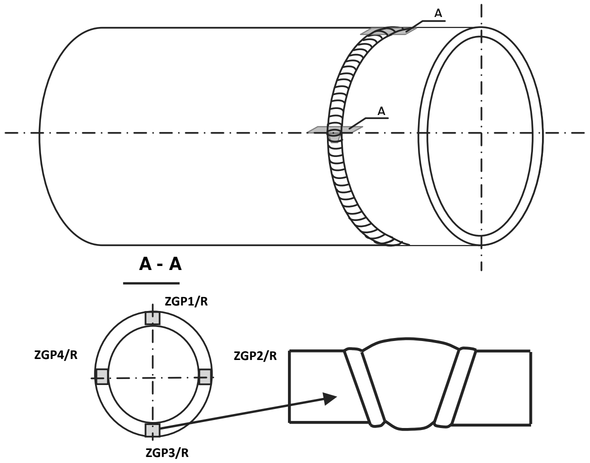

Fig. 5. Designation of area where HV10 hardness measurements and microstructure investigations of the material of 14MoV6-3 steel primary steam pipeline were made

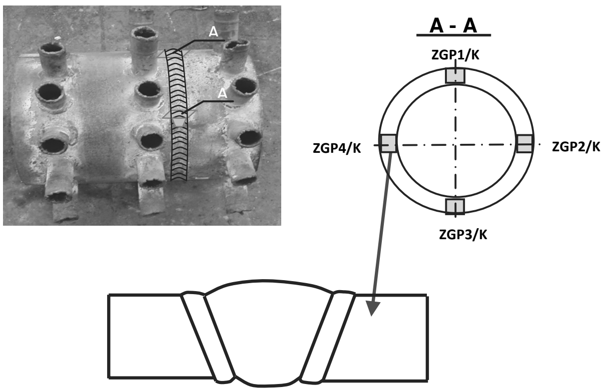

Fig. 6. Designation of area where HV10 hardness measurements and microstructure investigations of the material of 13CrMo4-5 steel inlet header were made

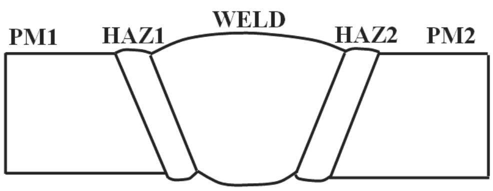

Fig. 7. Areas where microstructure photos of tested welded joints were taken. Symbols: PM - parent material, HAZ - heat-affected zone, W - weld

Within the examined structure of the materials of elements of 14MoV6-3 steel primary steam pipeline circumferential welded joint and 13CrMo4-5 steel II° secondary steam superheater header after service under creep conditions, neither discontinuities and micro-cracks nor initiation of processes of internal damages as a result of creeping were observed.

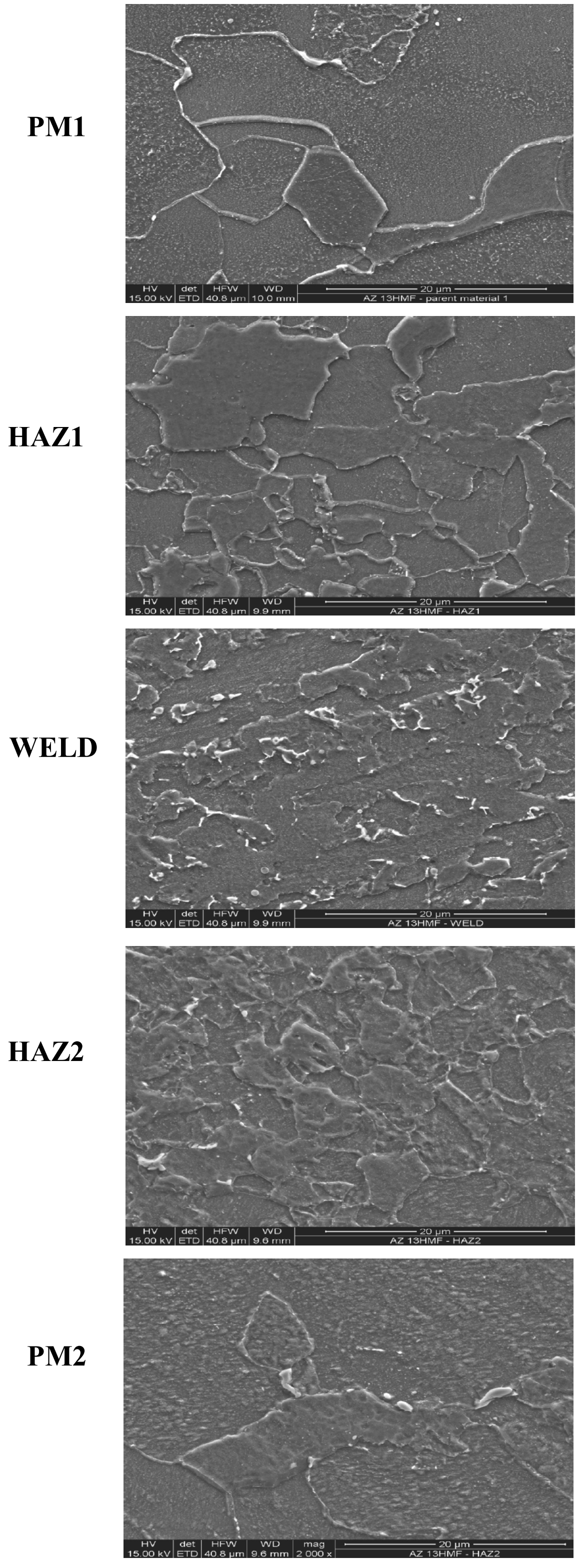

Fig. 8. Material structure of 14MoV6-3 steel welded joint after 200.000 h service. Investigation area marked as ZGP1/R

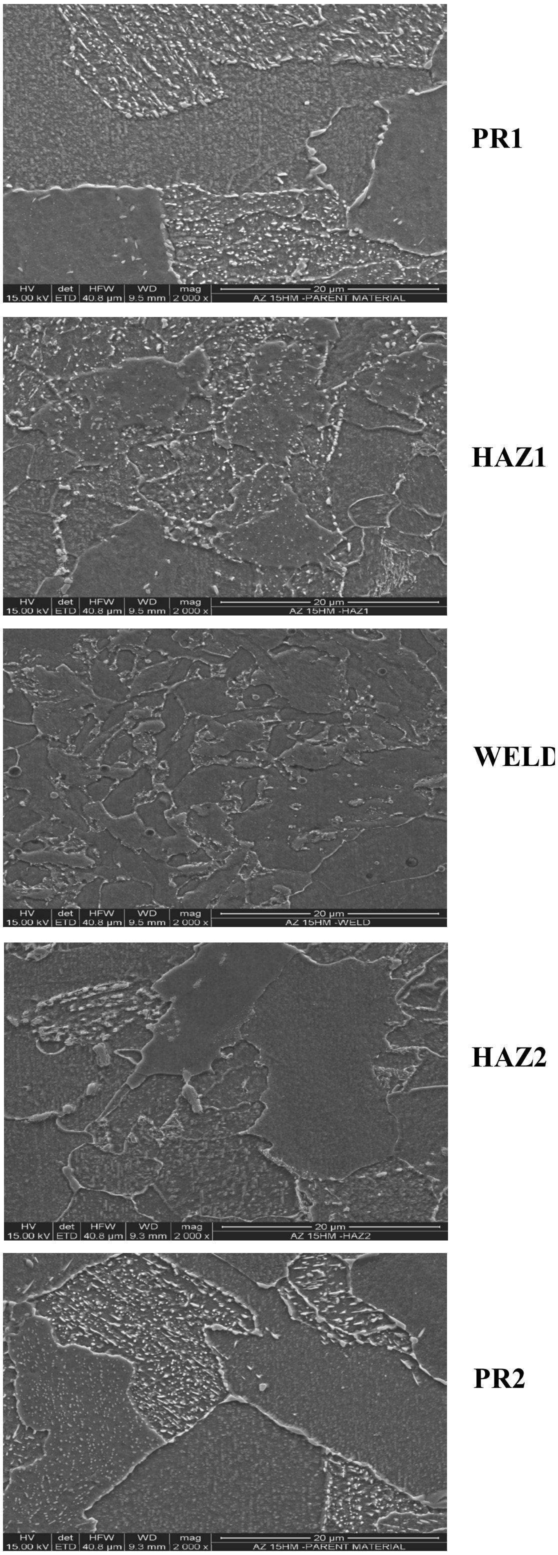

Fig. 9. Material structure of 13CrMo4-5 steel welded joint after 140,000 h service. Investigation area marked as ZGP1/R

Table 2.
Review of the results of investigations on microstructure of material of 14MoV6-3 steel welded joint

Area of investigation/ HV10	Description of microstructure Material condition – life exhaustion extent	HV10
Parent material 1	Ferritic-bainitic structure. Bainitic areas partially coagulated. At ferrite grain boundaries, few fine precipitations of different size. Precipitations inside ferrite grains, mostly very fine, distributed evenly within the structure. No discontinuities and micro-cracks observed in the structure. Bainitic areas: class I, precipitations: class a Destruction processes: class O CLASS 1/2, LIFE EXHAUSTION EXTENT: approx. 0.3	159
Parent material 2		153
HAZ 1	Heat-affected zone structure. No discontinuities and micro-cracks found in the structure.	167
WELD	Structure of welded joint weld material. No discontinuities and micro-cracks found in the structure.	218
HAZ 2	Heat-affected zone structure. No discontinuities and micro-cracks found in the structure.	172

Table 3.
Review of the results of investigations on microstructure of material of 13CrMo4-5 steel welded joint

Area of investigation/ HV10	Description of microstructure Material condition – life exhaustion extent	HV10
Parent material 1	Ferritic-pearlitic-bainitic structure. pearlite/bainite areas partially coagulated. At ferrite grain boundaries, numerous precipitations forming chains in places. inside ferrite grains, single fine precipitations. No discontinuities and micro-cracks observed in the structure. Pearlite/bainite areas: class I, precipitations: class a Destruction processes: class O CLASS 1/2, LIFE EXHAUSTION EXTENT: approx. 0.3	155
Parent material 2		157
HAZ 1	Heat-affected zone structure. No discontinuities and micro-cracks found in the structure.	166
WELD	Structure of welded joint weld material. No discontinuities and micro-cracks found in the structure.	197
HAZ 2	Heat-affected zone structure. No discontinuities and micro-cracks found in the structure.	197

No significant differences in the structure image of parent material of the examined elements depending on the investigation area (Figs. 5 and 6) were observed either. Therefore, the presented results of the structure and hardness investigations were only limited to metallographic microsections marked as ZGP1/R and ZGP1/K.

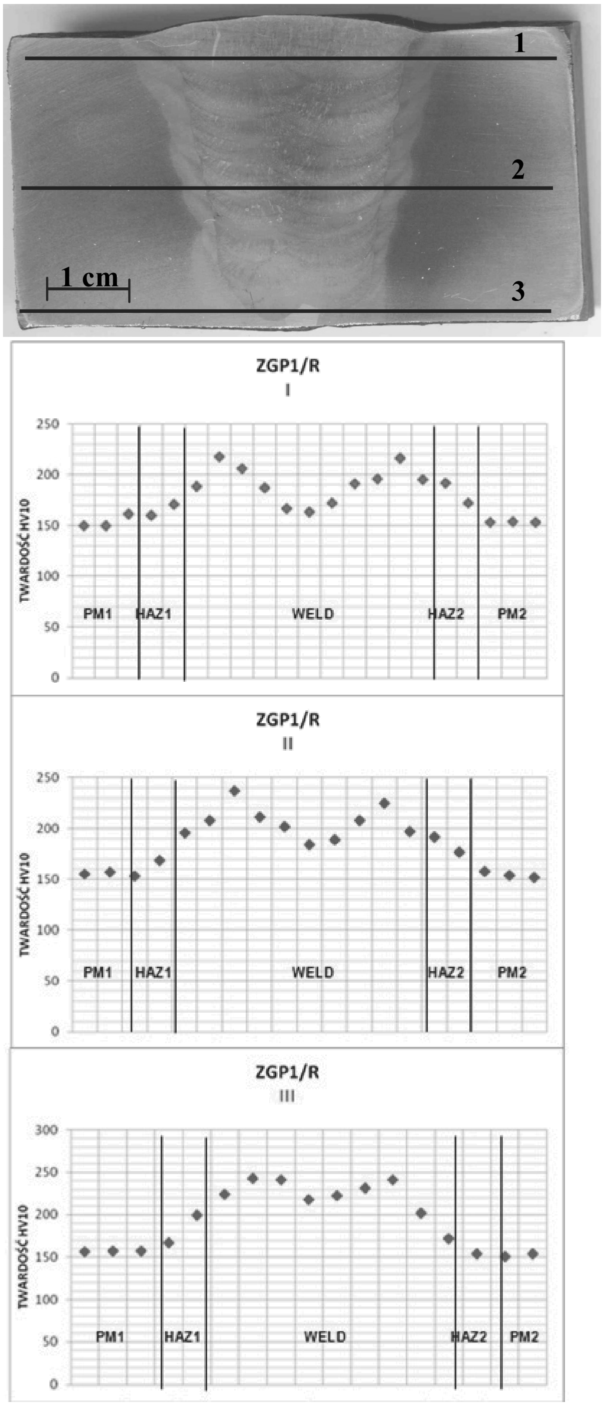

Fig. 10. Results of hardness tests of 14Mov6-3 steel primary steam pipeline welded joint. Testing area - transverse microsection marked as ZGP1/R. a) from the face side, b) in the middle of weld, c) from the root side

The hardness measurement by Vickers HV10 method was taken on transverse metallographic microsection of the examined circumferential welded joints of inlet header and primary steam pipeline. The results of hardness measurement HV10 against the background of macrophotograph of cross-section of the joints are shown in Figs. 10 and 11.

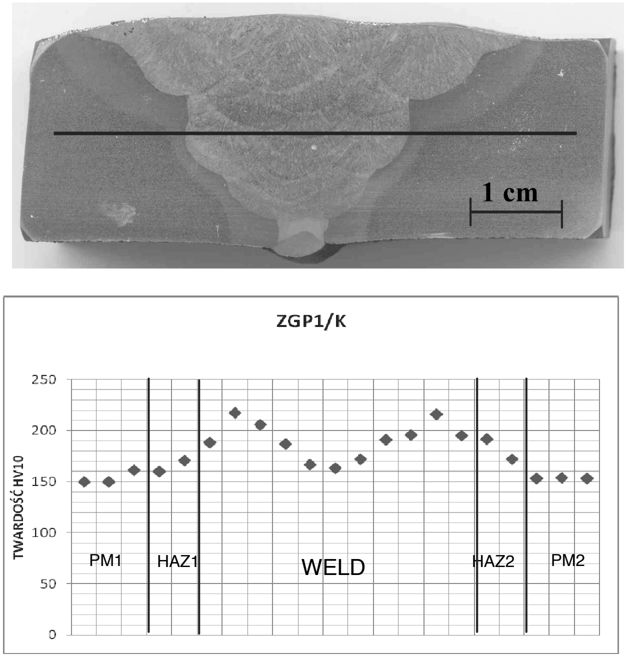

Fig. 11. Results of hardness tests of 13CrMo4-5 steel II° secondary steam superheater header welded joint. Testing area - transverse microsection marked as ZGP1/K.

Table 4.
Phase composition of carbides in material of the 14MoV6-3 steel pipeline after long-term service under creep conditions

Material condition	Phase composition of carbides
Initial state	M_3C+ MC
Service 200,000 h	V_8C_7 - main phase Fe_3C - very much Mn_2S - medium Mo_2C - medium $Cr_{23}C_6$ Isowit - little Cr_7C_3 - few Mo_3Fe_3C - trace

4.2. X-ray analysis of phase composition of carbide isolate precipitations

As a result of dissolving the matrix of the material of examined test piece of the primary steam pipeline and II° secondary steam superheater header by electrolytic method, carbides occurring in it were isolated. The X-ray phase analysis was carried out on the obtained carbide isolate to identify the existing carbides. The examinations were carried out with: Empyrean X-ray diffractometer using cobalt radiation in configuration with Pixcel detector. The obtained results are summarised in Table 4 and Fig. 12 for the primary steam pipeline test piece and in Table 5 and Fig. 13 for the II° steam superheater inlet header test piece, respectively.

Table 5.
Phase composition of carbides in material of the 13CrMo4-5 steel II° secondary steam superheater header after long-term service under creep conditions

Material condition	Phase composition of carbides
Initial state	M_3C+(M_2C)
Service 140.000 h	Fe_3C - main phase $Cr_{23}C_6$ Isowit - much Mo_2C - little Mn_2S - little Cr_7C_3 - trace Mo_3Fe_3C - trace

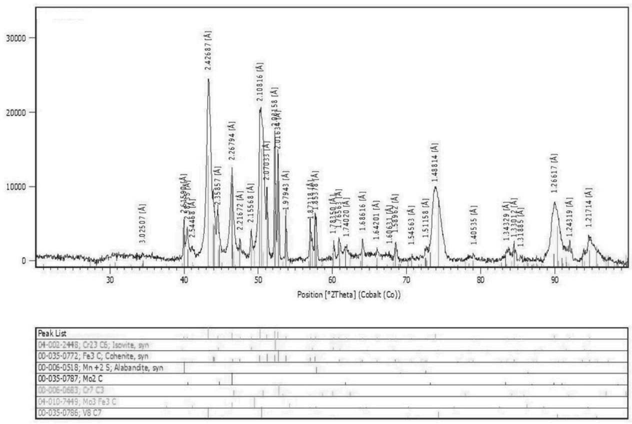

Fig. 12. Phase composition diffractogram for carbides in material of the 14MoV6-3 steel pipeline after long-term service under creep conditions

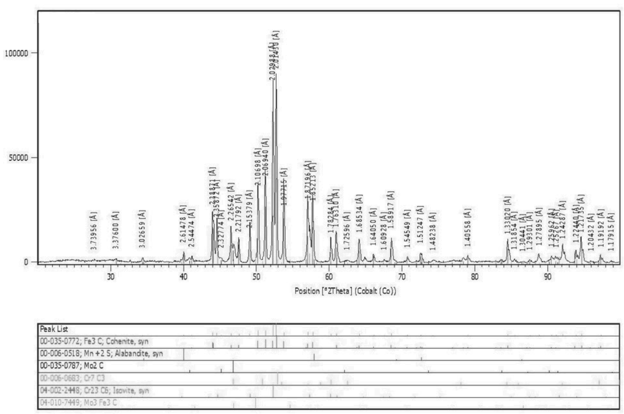

Fig. 13. Phase composition diffractogram for carbides in material of the 13CrMo4-5 steel II° secondary steam superheater header after long-term service under creep conditions.

The X-ray diffraction analysis of the deposit of carbides isolated electrolytically from the matrix of material of the examined test piece of the primary steam pipeline confirms the existence of significant amount of carbides, which are usually present in initial state as M_3C, and additionally M_8C_7 carbide as the main phase and slight amounts of M_2C, $M_{23}C_6$, M_7C_3 and Mo_3Fe_3C carbides and Mn_2S compound, as the result of simultaneous impact of high temperature and time due to service.

Whereas in case of analysis of the deposit of carbides isolated electrolytically from the matrix of examined material of the II° secondary steam superheater, the X-ray phase analysis confirmed the existence, in addition to M_3C (main phase) and M_2C carbides in initial state, of $M_{23}C_6$ carbides in large amount as well as M_7C_3 and Mo_3Fe_3C carbides (with slight content) and Mn_2S compounds as a result long-term service.

5. Conclusions

The characteristics of the examined 14MoV6-3 and 13CrMo4-5 steels after long-term service under creep conditions, with regard to changes in their structure, are the necessary elements for evaluation of the behaviour of materials and elements under operation which are made of them, especially after the design work time has been exceeded.

Developed by the Institute for Ferrous Metallurgy, the system for classification of structural changes and internal damages as a result of long-term service under creep conditions, correlated with the life exhaustion extent defined as a ratio of service time and time to destruction, allows the evaluation of suitability of critical elements of boiler for further service by the non-destructive matrix replica method.

Based on the results of investigations on structure, development level of carbide precipitation processes, development level of internal damage processes observed with scanning electron microscope as well as phase composition and content of carbide types using the X-ray phase analysis, the duration of safe service of the examined elements can be assessed for the working parameters of further service. The obtained investigation results are the element of the database of materials characteristics, which are successfully applied in the industrial practice for the condition evaluation of materials used in the pressure part of power boilers beyond the design work time and in the condition survey before the planned modernisation.

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