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Residual life of the (15HM) 13CrMo4-5 steel after 250 000 h service demonstrating internal damages in the form of voids

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ABSTRACT

Purpose: The purpose of the paper was to evaluate the material condition of the (15HM) 13CrMo4-5 steel after 250 000 h service under creep conditions demonstrating internal damages in the form of voids.

Design/methodology/approach: The investigations of microstructure using the scanning electron microscopy and investigations of mechanical properties at room and elevated temperature were carried out. The brittle fracture appearance transition temperature was determined based on impact tests.

Findings: The influence of long-term service under creep conditions on mechanical properties and structure degradation of 13CrMo4-5 steel was determined.

Practical implications: The applied methodology and adopted practice will be used for evaluation of condition and estimation of further operation of elements in the pressure part of power equipment working under creep conditions.

Originality/value: The obtained results of investigations are the elements of material characteristics developed by the Institute for Ferrous Metallurgy in Gliwice (Poland) for steels working under creep conditions.

Keywords: Mechanical properties; Structure; Degradation; Creep damages; Steel 13CrMo4-5

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PROPERTIES

1. Introduction

The availability and life of the power units is to a large extent affected by the condition of their critical elements, working under the most difficult conditions, with the highest temperature and stress parameters [1-6]. Out of the critical elements, those working above the limit temperature, i.e. under creep conditions, are of crucial importance.

In practice, more and more often there is a need to admit materials with initiated process of internal damages caused by creep to further service. It is dictated by the lack of possibility to make a new element during the repair cycle as well as the lack of possibility to repair it due to the condition of its material [1].

The nature of the process of initiation and development of internal damages depends on the operating stress and temperature level. Under real conditions, the stress and temperature level results in very slow changes in the microstructure over a very long time [7-17]. A simulation of such a condition is practically impossible. Therefore, the investigations carried out on material after real service are the source of important material data. Thus, the basic problem is to acquire the material for investigations with revealed initial stage of the development of internal damages caused by creep. The additional impediment in obtaining the material for investigations is the fact that the initiation and development of internal damages caused by creep is local, and not only with regard to the section of the element, but also to the area of its perimeter it occurs in.

This paper concerns issues related to admitting the critical elements of steam boilers, working under the most difficult temperature and stress conditions, including, but not limited to, the main and communication steam pipelines, to operation beyond the design service life. In particular, it includes issues related to evaluation of suitability for further operation of the materials after long-term service under creep conditions, demonstrating the initial stages of internal damages with regard to the formation and development of creep voids.

2. Material for investigations

The material for investigations was a specimen of the (15HM) 13CrMo4-5 steel steam pipeline elbow after approx. 250 000 h service under creep conditions with a damage in the form of cracking along the steam pipeline axis. The material for investigations is presented in Fig. 1.

Chemical composition of the examined pipeline material with reference to the requirements of standard specification is presented in Table 1.

The check analysis of chemical composition of the examined material was carried out 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 excitation optical emission spectrometry method using natural standards” with optical emission spectrometer Magellan Q8 by Bruker.

The results of check analysis of chemical composition revealed that the examined pipeline material after long-term service under creep conditions met the requirements of the standard with regard to chemical composition of the examined 13CrMo4-5 steel, except for the requirement for chromium Cr. The chromium content is much lower than the minimum level in accordance with the standard.

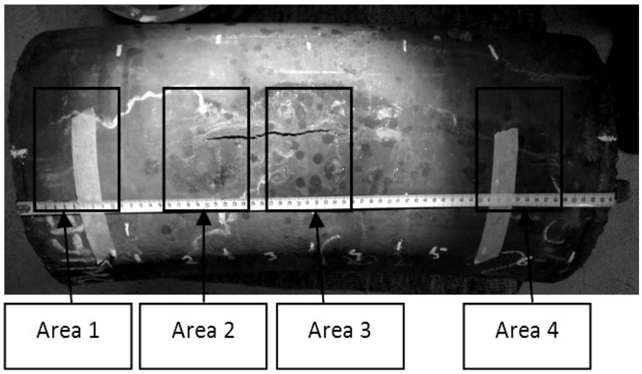

Fig. 1. Material for investigations in the form of the 13CrMo4-5 low-alloy steel steam pipeline specimen with visible damaged area and indicated sampling areas

3. Methodology of investigations

The scope of investigations included microstructure investigations in scanning electron microscope by non-destructive matrix replica method for identification of areas with internal damages in the form of voids. Drawing up the map of creep damages of the material after long-term service under creep conditions was made. Microstructure investigations in scanning electron microscope on metallographic microsections in areas with internal damages in the form of voids and with no damages were taken. Evaluation of microstructure condition of the examined material with regard to the degree of degradation as well as the state of development of carbide precipitation processes and development of internal damage processes was analyzed. Investigations of mechanical properties, in particular tensile strength, yield point, elongation and yield point at elevated temperature, in areas with internal damages in the form of voids and with no damages were made. X-ray analysis of phase composition of the precipitated carbide isolates was investigated.

These investigations are necessary to evaluate the real life time of the materials of equipment working under creep conditions with revealed internal damages in the form of voids.

Table 1.
Check analysis of chemical composition of the examined specimen material after long-term service under creep conditions

Grade of material	Content of elements [%]									
	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	others
PN-75/H-84024 13CrMo4-5	0.11 0.18	0.40 0.70	0.15 0.35	max 0.04	max 0.04	max 0.25	0.70 1.00	max 0.35	0.40 0.55	Al max 0.02
13CrMo4-5 after 250 000 h	0.17	0.55	0.24	0.018	0.023	0.20	0.49	0.089	0.53	Al <0.005

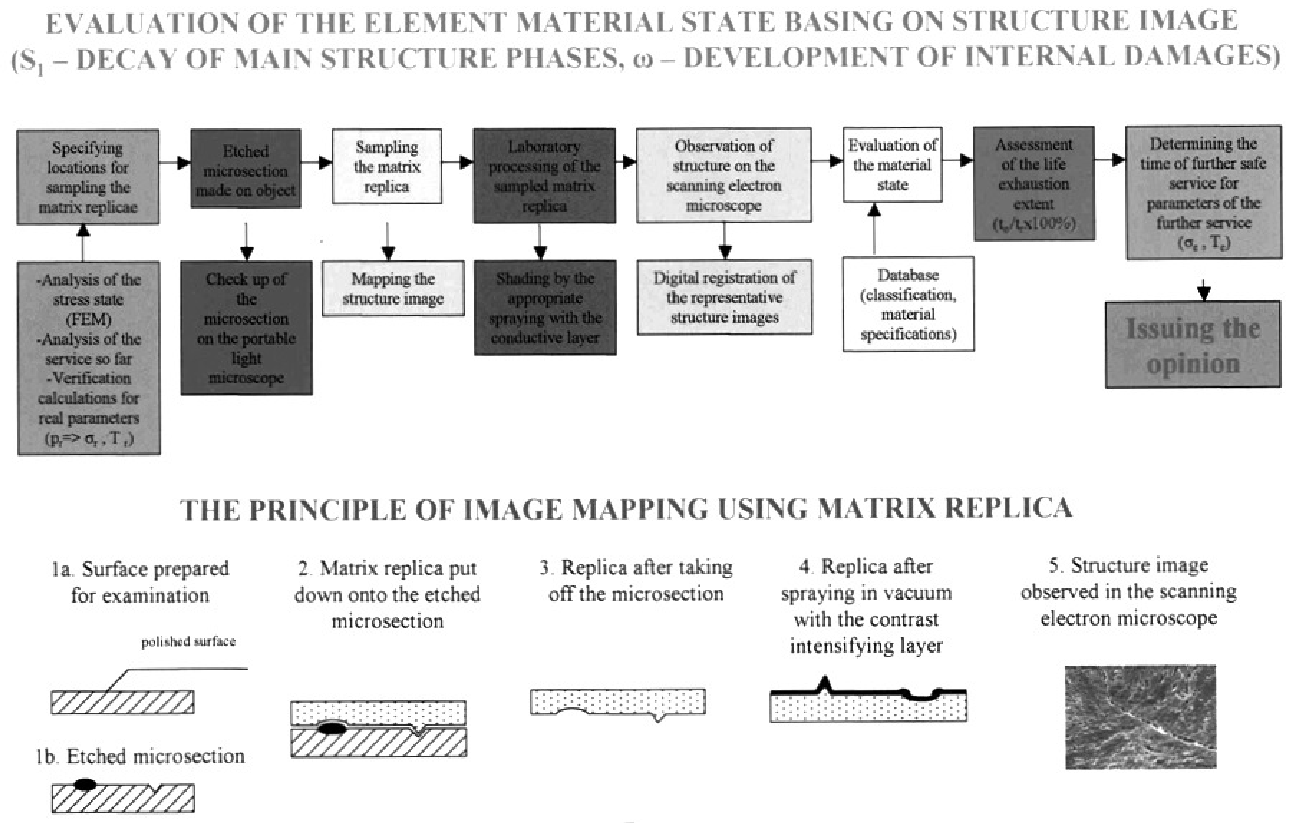

Fig. 2. Method for evaluation and the principle of image mapping by matrix replica

4. SEM investigations of microstructure by non-destructive matrix replica method

To identify the areas with internal damages in the form of voids within the material after long-term service under creep conditions, the structure investigations were carried out by the matrix replica method (Fig. 2) using the scanning electron microscope Inspect F with magnifications of 500 to 5000x.

The areas where microstructure investigations by the matrix replica method were carried out are marked as areas 1-4 according to Figure 1.

The example results of investigations in the form of microstructure images obtained by the matrix replica method for the examined steam pipeline after long-term service under creep conditions are shown in Figure 3, respectively.

The internal damage processes are local, therefore to reveal the area of their occurrence within the examined pipeline specimen material, the investigations were carried out within the indicated areas of the pipeline material. For each of the examined areas (area 1-4) the evaluation of material condition, including the internal damages, was made in accordance with the Institute for Ferrous Metallurgy's own classification. Based on the microstructure investigations by the matrix replica method, the areas of the pipeline material with creep voids and with no internal damages were distinguished.

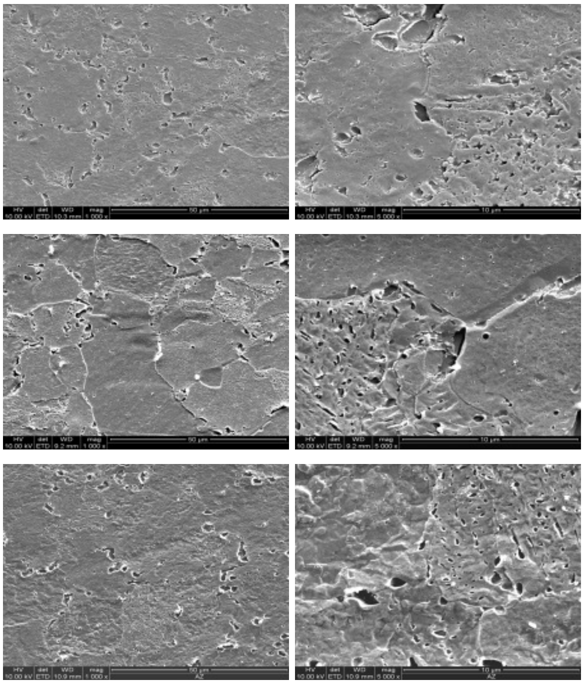

Fig. 3. Structure of the steam pipeline specimen material: a) with no internal damages (area 4); b) with internal damages in the form of voids (area 1); c) with internal damages in the form of micro-cracks (area 3) - SEM replica

5. SEM investigations of microstructure on metallographic microsections

The proper microstructure investigations were performed on metallographic microsections. The microsections made on cross-section of the specimen of the examined element were prepared by mechanical grinding and polishing followed by etching in areas determined based on the results of investigations by the non-destructive matrix replica method provided in chapter 4. The observations were made using the scanning electron microscope Inspect F with magnifications of 500 to 5000x.

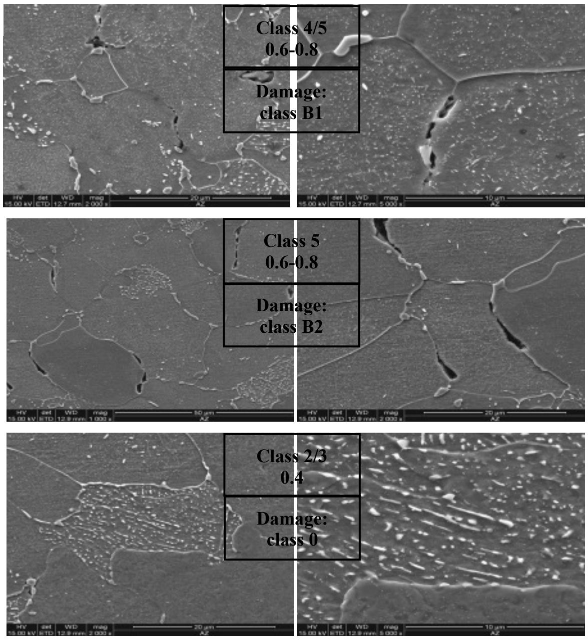

Fig. 4. Microstructure of the steam pipeline specimen material over the element thickness within the area beyond the external damage (area 1): a) external surface; b) middle surface; c) internal surface - SEM microsection

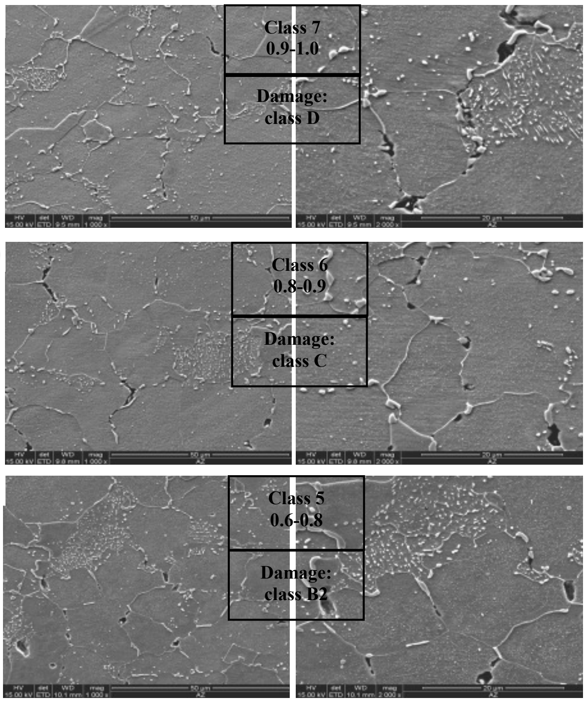

Fig. 5. Microstructure of the steam pipeline specimen material over the element thickness within the area with external damage (area 3): a) external surface; b) middle surface; c) internal surface - SEM microsection

The microstructure investigations were carried out over the element thickness within the area beyond the external damage and within the external damage area (Fig. 1. area 1, area 3). The results of investigations in the form of selected microstructure images for the examined steam pipeline after long-term service under creep conditions are shown in Figs 4-5, respectively.

6. X-ray analysis of phase composition of precipitated carbide isolates

The following carbides were isolated by dissolving the matrix of the examined steam pipeline specimen material after long-term service under creep conditions by the electrolytic method.

The X-ray phase analysis was carried out on the obtained carbide isolate and carbides were identified. The investigations were carried out with Empyrean X-ray diffractometer using cobalt radiation in configuration with Pixcel detector.

The obtained results of investigations for the examined 13CrMo4-5 steel pipeline specimen material are summarised in Table 2.

The analysis of deposit of carbides isolated electrolytically from the matrix of the examined 13CrMo4-5 steel steam pipeline material revealed the existence of significant amount of $M_{23}C_6$ carbides as the main phase, large amount of M_3C cementite as well as insignficant amount of M_2C and trace amount of M_7C_3 carbides as an effect of long-term service at high temperature.

Table 2.
Phase composition of carbides in the 13CrMo4-5 steel steam pipeline specimen material after long-term service under creep conditions

Material condition	Phase composition of carbides	Precipitation sequence
As-received condition	M_3C, M_2C	$M_3C + (M_2C)$
Service 250 000 h	$Cr_{21}Fe_2C_{6\ Isovit}$ - main phase Fe_3C cementite - large amount Mo_2C - small amount, Cr_7C_3 - trace amount	$M_{23}C_{6\ m.ph} + M_3C_{\ lg} + M_2C_{\ sm} + M_7C_{3trace.}$

7. Mechanical properties

For the examined specimen of steam pipeline after long-term service under creep conditions the evaluation of strength and plastic properties was made at room and elevated temperature (T_b = 20, 500°C). Additionally, within the area of internal damages in the form of voids in the steam pipeline material the investigations of the above-mentioned properties were carried out at T_b = 200, 300, 400, 450°C.

The strength test pieces were taken from area 1 with confirmed internal damages and from area 4 without confirmed internal damages in the material in accordance with Figure 1.

The investigations of strength properties were carried out in tensile test at room temperature to determine the tensile strength (R_m), yield point (R_e), elongation (A_5) and reduction of area (Z) and at elevated temperature to determine the tensile strength (R_m^t), yield point (R_e^t), elongation (A_5^t) and reduction of area (Z^t).

Table 3.
Results of investigations of strength properties

Test area	Grade of steel to DIN (PN) Dimensions, mm	Mechanical properties			
		R_m	$R_{p0.2}$	A_5	$R_{p0.2}^{500°C}$
		MPa	MPa	%	MPa
1	2	4	5	6	7
within the area of damages	13CrMo4-5 ϕ 57 x 4	472	289	$27^{20°C}$ $31^{500°C}$	195
within the area with no damages confirmed		491	311	$28^{20°C}$ $30^{500°C}$	227
Requirements for material in the as-received condition acc. to PN-74/H-74252		440-570	min 295	min 22	min 176

The results of these investigations at room temperature are summarised in Table 3, columns 4-6, while the results for yield point R_e^t at the temperature T_b = 500°C, which is similar to the service temperature - in column 7 of the above-mentioned table.

The results of investigations of strength properties at the temperature T_b = 200, 300, 400, 450°C for the steam pipeline material within the area of internal damages in the form of voids are presented in Figure 6.

The impact tests were carried out on transverse test pieces with V notch cut perpendicularly to the jacket surface. The impact test pieces were taken from area 1 with confirmed internal damages and from area 4 without confirmed internal damages in the material in accordance with Figure 1.

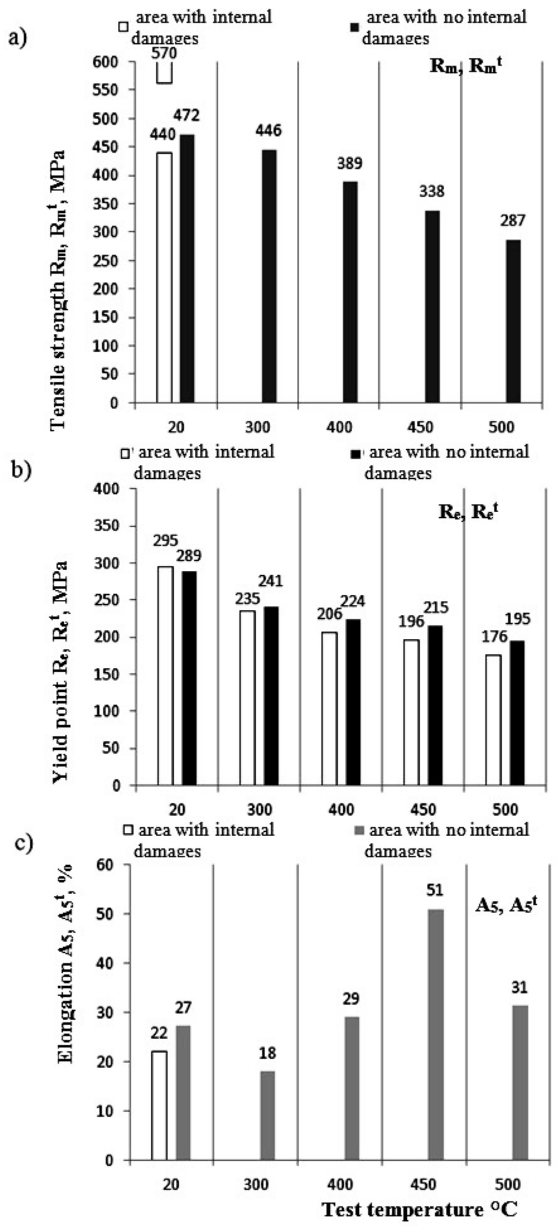

Fig. 6. Relationship between strength properties of the examined 13CrMo4-5 steel steam pipeline specimen material after 250 000 h service from test temperature T_b within the area of internal damages in the material, in particular: a) tensile strength R_m^t, b) yield point R_e^t, c) elongation A_5

The obtained results of impact energy tests depending on test temperature are presented graphically in Fig. 7. The tests were carried out for three temperature levels: 20, 40 and 60°C. Fig. 7a shows the impact energy results obtained for the examined steam pipeline specimen material within the area of internal damages, while Figure 7b – within the area with no internal damages caused by creep. Their comparison is shown in Figure 8.

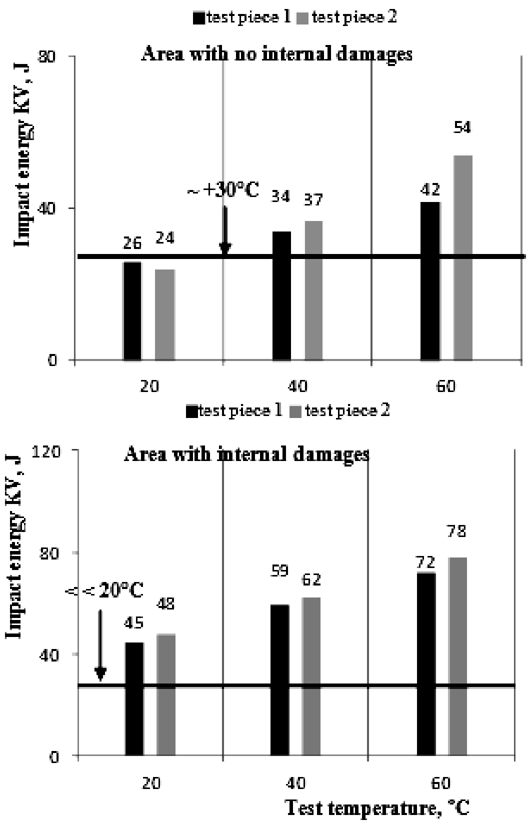

Fig. 7. Test results of impact energy measured on V-notch samples depending on test temperature of the steam pipeline specimen: a) within the area of internal damages; b) within the area with no damages confirmed

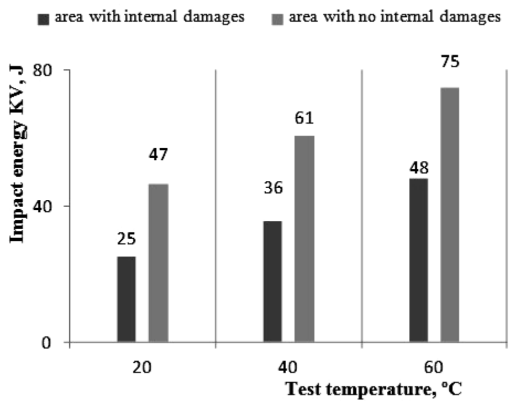

Fig. 8. Comparison of impact energy results for the 13CrMo4-5 steel steam pipeline specimen material tested within the area of internal damages to impact energy results measured within the area with no internal damages confirmed

8. Conclusions

Based on SEM investigations of microstructure by non-destructive matrix replica method, the areas with internal damages in the form of voids were identified in the material after service. As the internal damage processes are local, a map of internal damages caused by creep was drawn up to reveal the areas of their occurrence within the examined pipeline specimen material.

The condition evaluation the material with revealed creep voids after 250 000 h service was made based on joint assessment of the obtained results of investigations of mechanical properties and microstructure.

The investigations of microstructure carried out over the steam pipeline element thickness allowed the state of development of carbide precipitation processes and development of internal damages (Figs 4, 5) to be assessed. The nature of stresses in case of pipeline elements causes that higher structure degradation and initiation of internal damage processes should be expected on the external side, which is confirmed by test results. For area beyond the visible internal damage the oriented voids (class B1) were observed on the external side, while on the internal side no internal damages were observed (class O). For area with visible internal damage micro-cracks (class D) were observed on the external side, while on the internal side there were the coalescences of voids (class B2).

The type and share of precipitates revealed during the X-ray phase analysis corresponds to the exhaustion degree estimated based on the image of microstructure (Table 2).

The sequence of carbides within the examined material revealed based on the X-ray diffraction analysis of electrolytically isolated deposits confirms the class of microstructure determined based on the analysis of observed microstructure images.

The investigations of mechanical properties revealed that tensile strength obtained for the material with damages in the form of creep voids at room temperature is slightly above the minimum level required for material in the as-received condition. At elevated temperature, it is on satisfactory level too. The yield strength values obtained at elevated temperature are slightly above the minimum level required for material in the as-received condition. Only at room temperature, the obtained value is slightly below the minimum one required for material in the as-received condition. In addition, the elongation level in tensile test at room temperature is above the required minimum value for the as-received condition, which is 22%. At test temperature of 300°C, the values of 18% were obtained, while at other temperature levels - the values were well above the requirements for the as-received condition at room temperature. Low elongation value at 300°C and diverse values at other test temperature levels may be the evidence of non-uniform distribution of creep voids within the examined material after service.

In accordance with expectations, the impact energy of the material after service with creep voids is much lower, regardless of the test temperature level, than that obtained for the same material after service without internal damages, characterised by identical state of disintegration of pearlite areas and state of development of carbide precipitation processes. It represents approx. 50% of the values obtained for the material with no creep voids. The significant difference also occurred at the determined brittle fracture appearance transition temperature, although it was obtained on limited number of test pieces and limited number of test temperature levels. The determined brittle fracture appearance transition temperature for the material with no creep voids is negative and much below room temperature, whereas for the material after service with creep voids, this temperature is positive and equals to approx. + 30°C.

These investigations are necessary to evaluate the real life time of the materials of equipment working under creep conditions with revealed internal damages in the form of voids.

The obtained results of investigations will enrich the characteristics of the examined 13CrMo4-5 steel with data on residual life for steel with creep voids.

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME’2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

References

[1] J. Dobrzański, Materials science interpretation of the life of steels for power plants, Open Access Library 3 (2011) 1-228.

[2] A. Hernas, J. Dobrzański, Life-time and damage of boilers and steam turbines elements, Publishing House of the Silesian University of Technology, Gliwice, 2003 (in Polish).

[3] A. Hernas, Materials and technologies for construction of supercritical boilers and waste incinerators, Joint publication edited by A. Hernas, Katowice, 2009.

[4] J. Dobrzański, B. Kowalski, J. Wodzyński, Technical diagnostics of critical components in the pressure part of power boilers working under creep conditions after exceeding the design work time, Current problems related to construction and operation of boilers; Silesian University of Technology, IMiUE 23 (2009) 85-126.

[5] J. Dobrzański, A. Zieliński., H. Krztoń, Mechanical properties and structure of the Cr-Mo-V low-alloyed steel after long-term service in creep condition, Journal of Achievements in Materials and Manufacturing Engineering 23/1 (2007) 39-42.

[6] J. Dobrzański, H. Krztoń, A. Zieliński, Development of the precipitation processes in low-alloy Cr-Mo type steel for evolution of the material state after exceeding the assessed lifetime, Journal of Achievements in Materials and Manufacturing Engineering 23/2 (2007) 19-22.

[7] M. Dziuba-Kałuża, J. Dobrzański, A. Zieliński: Life time of circumferential welded joints of critical elements of Cr-Mo and Cr-Mo-V low-alloy steel boilers after long-term service beyond the design time, Transactions of the Institute for Ferrous Metallurgy 65/3 (2013) 64-66.

[8] A. Zieliński, J. Dobrzański, M. Dziuba-Kałuża, Structure of welded joints of 14MoV6-3 and 13CrMo4-5 steel elements after design work time under creep conditions, Archives of Materials Science and Engineering 61/2 (2013) 69-76.

[9] G. Golański, A. Zieliński, A. Zielińska-Lipiec, Degradation of microstructure and mechanical properties in martensitic cast steel after ageing, Materialwissenschaft und Werkstofftechnik 46 (2015) 248-255.

[10] A. Zieliński, G. Golański, M. Sroka, T. Tański, Influence of long-term service on microstructure, mechanical properties, and service life of HCM12A steel, Materials At High Temperatures (2015) doi: 10.1179/1878641315Y.0000000015

[11] A. Zieliński, G. Golański, M. Sroka, J. Dobrzański, Estimation of long-term creep strength in austenitic power plant steels, Materials Science and Technology (2015) doi:10.1179/1743284715Y.0000000137

[12] G. Golański, A. Zieliński, J. Słania, J. Jasak, Mechanical properties of vm12 steel after 30 000 hrs of ageing at 600°C temperature, Archives of Metallurgy and Materials 59 (2014) 1357-1360.

[13] A. Zieliński, J. Dobrzański, H. Purzyńska, G. Golański, Properties, structure and creep resistance of austenitic steel Super 304H, Materials Testing 57 (2015) 859-865.

[14] A. Zieliński, G. Golański, The influence of repair welded joint on the life of steam pipeline made of Cr-Mo steel serviced beyond the calculated working time, Archives of Metallurgy and Materials 60 (2015) 1045-1049.

[15] A. Zieliński, M. Dziuba-Kałuża, J. Dobrzański, M. Sroka, The impact of repair welded joint on the life of Cr-Mo-V steel steam pipeline after service under creep conditions, Archives of Materials Science and Engineering 68/1 (2014) 36-44.

[16] M. Sroka, A. Zieliński, Matrix replica method and artificial neural networks as a component of condition assessment of materials for the power industry, Archives of Materials Science and Engineering 58/2 (2012) 130-136.

[17] J. Dobrzański, M. Sroka, Computer aided classification of internal damages the chromium-molybdenum steels after creep service, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 143-146.