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Estimation of the residual life of L17HMF cast steel elements after long-term service

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Properties

ABSTRACT

Purpose: of this paper is to present the changes of the mechanical properties and structure in material components of the power station boiler after long-term creep service made of G17CrMoV5-10 low-alloyed cast steel.

Design/methodology/approach: The material of the research studies has been obtained from Polish power stations. Examined element has exceeded their assessed life of 105.000 hours. Mechanical properties and structure examinations were carried out on material after long-term service in creep conditions. The microstructure has been observed using a light and a scanning electron microscope. The investigation of the development of the precipitation processes was done by X-ray diffraction phase analysis.

Findings: The microstructures and phase compositions of the residues, obtained from the elements, depend on life exhaustion extent.

Practical implications: The presented method can be used for evaluation and qualification of structural changes in power station boiler and turbine components operating in creep conditions.

Originality/value: The paper presents results of changes in the mechanical properties, structure and in the precipitation processes which are applied to evaluation for the condition of the elements in further industrial service.

Keywords: Mechanical properties; Structure phase analysis; Degradation after creep service; Residual life

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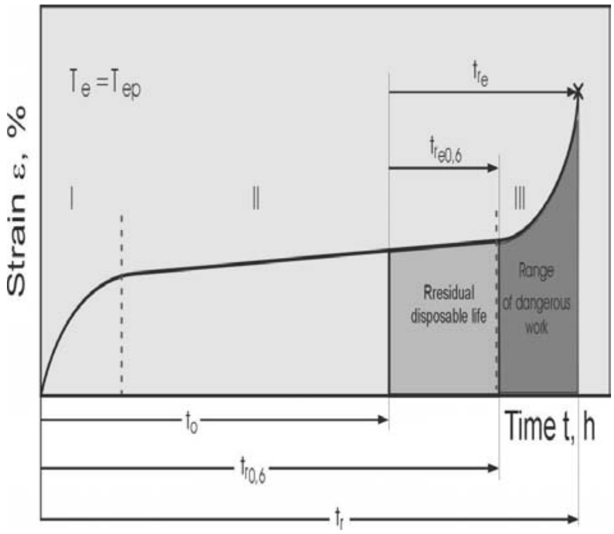
1. Introduction

The issue of forecasting the life of steel elements applied in power industry is the subject of examination in many research centres [1-15].

Currently in Poland a great majority of power units has reached or exceeded their design life of 100 000 or 200 000 hours significantly. Thus, development of diagnostic examinations of the boilers' critical elements is reasonable, since their purpose is to allow for the boilers' further safe and failure-free service above the estimated time of operation [10].

Reliability of the power unit mostly depends on the condition of the most important construction elements called critical elements, which cannot be replaced during technical survey due to their construction. These elements include: boiler drums, steam superheater headers, as well as the main and communication transfer steam pipelines consisting of straight sections, elbows, T-pipes, pipe-crosses and branch-joints. Therefore, it is very important to introduce periodical diagnostic examinations which enable planning repairs or replacements of element or group of elements on the basis of performed material research, mostly non-destructive ones.

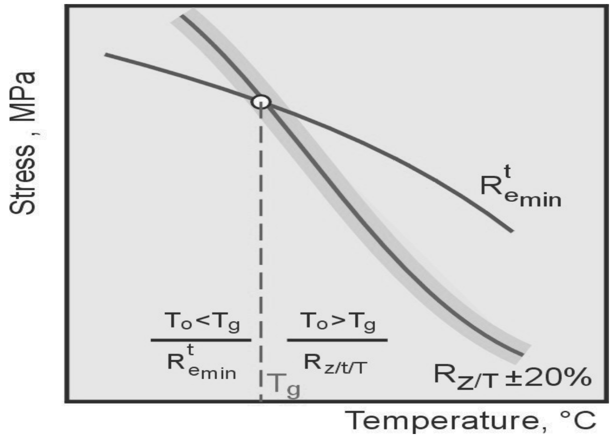
Service life of pressure elements of the power devices often differs from the design life significantly. It is mostly connected with the actual higher creep resistance, than its average value according to standard requirements, assumed in construction calculations. A significant role in the assessment of the material's service life is played by the microstructure which is subject to changes due to a long-term influence of temperature and stress, and as a result has a considerable effect on the life of construction element. Creep resistance for elements operating under such temperature conditions, i.e. above limiting temperature, is its main material attribute which decides about its usability for further operation. The constructor as well as the user is interested mostly in the time of safe and efficient service called disposable life. It is related to the term residual life understood as the time difference between actual and calculative material life; whereas the safe operation time after exceeding the calculative time is a part of residual life called residual disposable life. It is defined as the time of operation after exceeding the calculative one till the end of the II creep period for parameters of extended operation. Schematic depiction of the life of elements operating under creep conditions, is shown in Fig. 1. In practice the disposable life of construction elements is in most cases bigger than the calculative life, sometimes a few times bigger.



t_o – calculative operation time,
$t_{r0,6}$ – disposable operation time,
t_r – time to rupture,
t_{re} – residual life,
$t_{re0,6}$ – disposable residual life

Fig. 1. Schematic depiction for definition of the residual and the disposable life [2]

Therefore, for construction elements during operation time the main factor influencing structure changes is creeping. The most credible results, when forecasting the life, are obtained on the basis of the material's creep tests in the initial condition as well as after long term operation. These tests still constitute the main source of information in the assessment of life and the residual life of materials operating at the temperature higher than the limiting temperature. T_g per the calculative time of operation, i.e. materials designed on the basis of allowable stress values k determined out of the average time creep strength $R_{z/t/T}$ or creep limit $R_{x/t/T}$. Graphic method of determining the limiting temperature is illustrated in Fig. 2.



T_o – calculative temperature,
T_g – limiting temperature.

Fig. 2. Determining method for limiting temperature [2]

The duration time of long-term creep tests ranges from minimum few to a few dozen thousand hours, thus the time of waiting for results is minimum several years. In order to shorten the time of performing creep tests and assessment of life or residual life, there are special tests applied in engineering, the so called advanced creep tests with duration time ranging from few dozen hours to several thousand hours. It enables obtaining test results within maximum a dozen months or so, with the possibility of making a reliable assessment of an element's residual life and determining safe time of its further operation [5].

2. Materials for investigation

Investigated material included T-pipes taken from a fresh steam pipeline after long-term operation under creep conditions. The elements were made of G17CrMoV5-10 (L17HMF) low-alloy cast steel. Results of research on the T-pipe material, whose service time slightly exceeded the calculative 100 000 hours, are shown below. Service parameters and time of previous operation of the investigated material are given in Table 1.

Chemical composition of the T-pipe's material with reference to the requirements of PN – EN 10213-2 standard for the investigated cast steel is listed in Table 2.

Table 1.
Material for investigation - service parameters and type of the investigated element

No	Element/material	Service time [h]	Service parameters	
			Design pressure p_o [MPa]	Design temperature T_o [°C]
1.	T-Connection/ G17CrMoV5-10	105 000	17.6	535

Table 2.
Material for investigation -chemical composition of the examined material from the G17CrMoV5-10 cast steel

	Chemical composition [wt., %]								
	C	Mn	Si	P	S	Cr	Ni	Mo	V
The examined T-pipe material	0.15-0.20	0.50-0.90	max 0.60	max 0.020	max. 0.015	1.20-1.50	-	0.90-1.10	0.20-0.30
PN-89/H-83157	0.18	0.69	0.33	0.018	0.015	1.29	0.050	1.04	0.31

3. Mechanical properties and structure after long term creep service

3.1. Mechanical properties

Results of research on the mechanical properties of the T-pipe material made of G17CrMoV5 - 10 low alloy cast steel after long term operation under creep conditions in comparison with the requirements for the material in the initial condition are presented graphically in Fig. 3.

Performed research has shown that the examined cast steel after operation meets the standard requirements concerning tensile strength and yield point determined at room temperature. Yield point determined at 535°C is comparable with the one established in standard requirements for the temperature of 550°C (260 MPa).

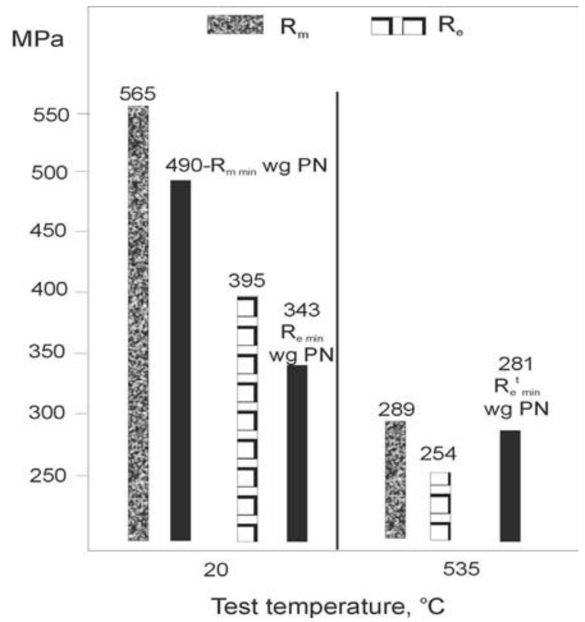


Fig. 3. Mechanical properties at room and elevated temperature of G17CrMoV5-10 low-alloyed cast steel after long term service

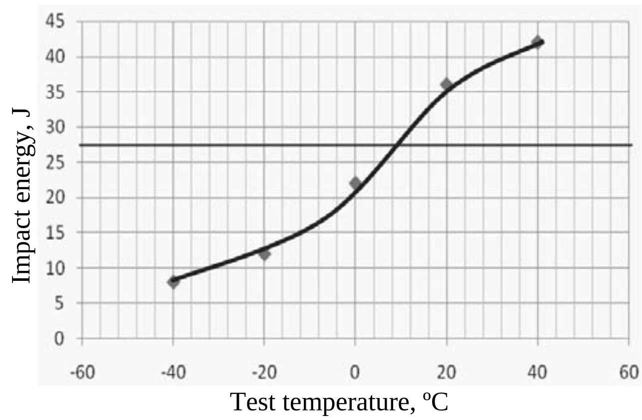


Fig. 4. DBTT temperature for G17CrMoV5-10 cast steel after 105 000 h of operation under creep conditions

The research on impact energy was carried out on longitudinal samples with V-notch. The research took place at the temperature from -40 to 40°C. The purpose was to determine NDT temperature for the examined material. Change of impact energy depending on the investigation temperature with the determined DBTT temperature for examined material is illustrated in Fig. 4. The transition temperature for examined cast steel was ca. +10°C. Hardness of the investigated material after operation amounted to 177 HV10.

3.2. Determining the residual life in the advanced creep tests

Advanced creep tests were carried out on single-sample, six-user-station machines used for creep tests and multi-sample machines for creep tests of IFM - IPM production or IFM production, with a modified system of regulation and temperature measuring.

Obtained results of tests are presented in Fig. 5 graphically in the form of interrelation log t_{re} = $f(T_b)$. These results made it possible to determine the residual life - by the graphical extrapolation method - for the examined T-pipe material under the test stress of σ_b = 60 MPa being at the same time the assumed stress level for further operation. The results also enabled determining of the disposable residual life for operating parameters of further service (p_r, T_r) and finally on the basis of these parameters the safe operation time was estimated for the examined element (Table 3).

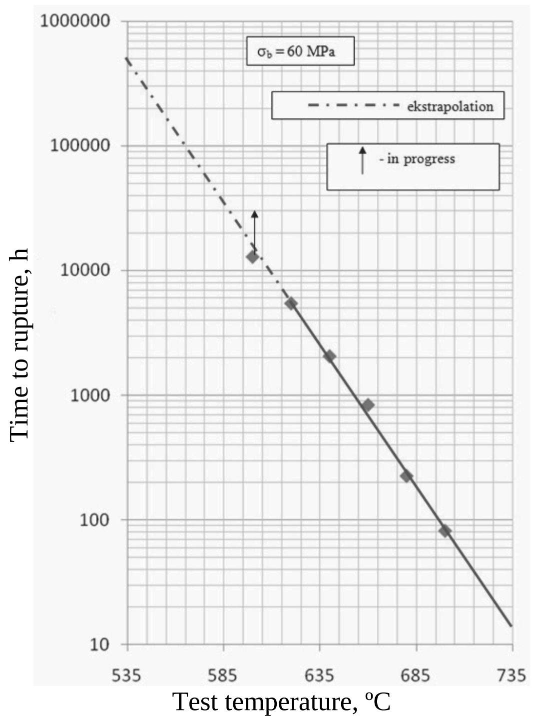


Fig. 5. Results of advanced creep tests of G17CrMoV5-10 cast steel after 105 000 hours of operation under creep conditions

Table 3.
The forecast residual life for T-pipe after 105 000 hours of operation under creep conditions on the basis of advanced creep tests

Element/ material	Assumed operating stress σ_r [MPa]	Assumed temperature of further operation T_r [°C]	Estimated life [h]	
			Residual life t_{re}	Disposable residual life t_b
T-Connection/ G17CrMoV 5-10	60	535	500 000	275 000
		540	380 000	209 000

3.3. Analysis of changes in microstructure as a result of long-term operation

The investigated cast steel after operation was characterized by the bainitic - ferritic structure. Image of the microstructure of G17CrMoV5 - 10 cast steel observed on the optic microscope at magnifications of up to 1000x is similar to the structure of new casts. (Fig. 6a). Only after observations on the scanning microscope at magnifications from 2000 up to 3000x it could be noticed that the investigated cast steel's operation had contributed to a slight decay of bainite areas through coagulation of precipitates in those areas as well as to the increase of carbide precipitations on grain boundaries, where some "chains" of precipitations could be observed (Figs. 6b, c). Other noticed changes were: depletion inside ferrite grains into fine-dispersion precipitations and occurrence of larger unequally located coagulated precipitates.

a)
b)
c)

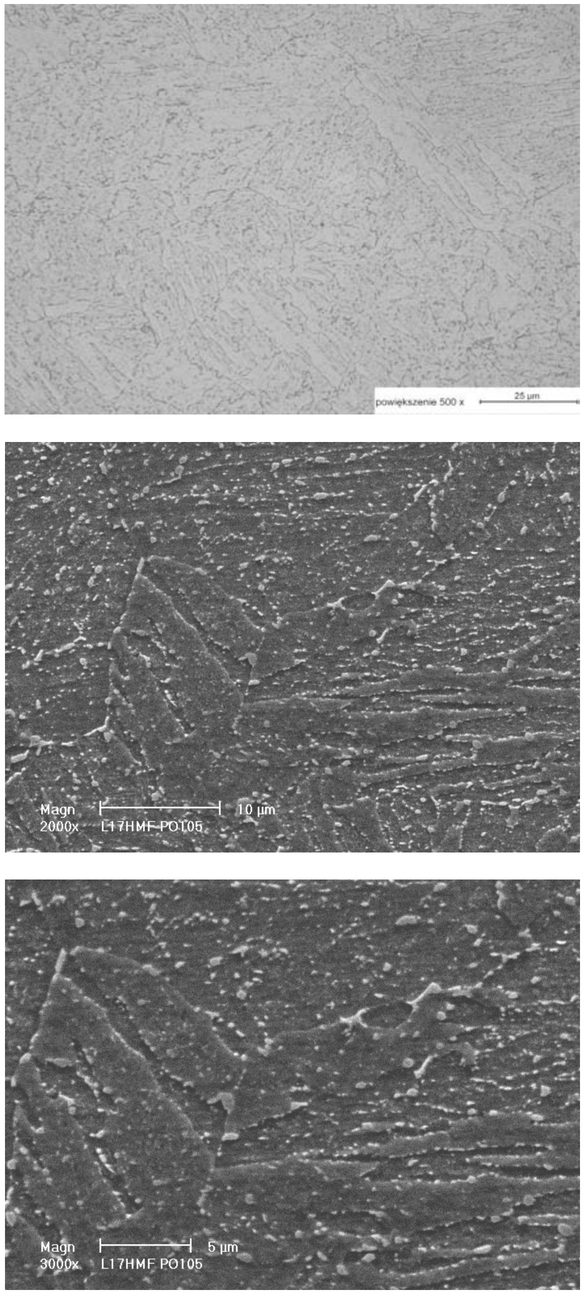
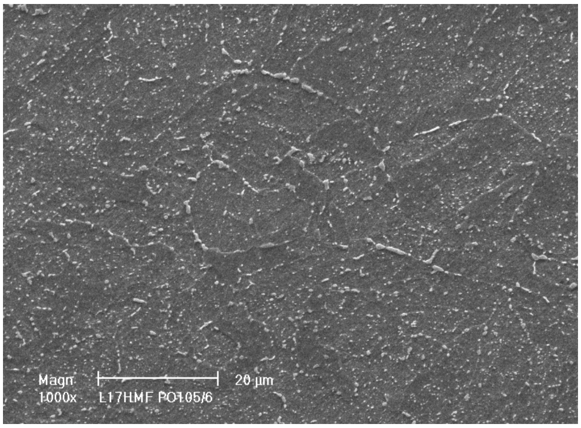


Fig. 6. Structure of T-pipe material made of low alloy G17CrMoV5-10 cast steel; after 105 000 hours of operaiton. Hardness 177 HV10. a) microsection LM, magnification 1000x. b) SEM microsection, magnificaiton 2000x, c) microsection SEM, magnification 3000x

Significant structure changes visible on the optic microscope were observed in the T-pipe material subject to shortened creep tests (Figs. 7-11). The performed creep test of the investigated cast steel caused further change in the structure of the examined T-pipe material. These above-mentioned changes were: decay of bainite areas into ferrite with carbide precipitations and increase of size of the carbides precipitated inside grains as well as on ferrite grain boundaries. Moreover, in the post-bainite areas characteristic arrangement of carbides was observed.

Performed structural research on the G17CrMoV5 – 10 (L17HMF) cast steel after 105 thousand hours of operation under creep conditions, subject to shortened creep tests at the temperature higher that the temperature of operation and under the test stress similar to the operating stress, has revealed a significant influence of test duration time and temperature on the changes in structure.

a)



b)

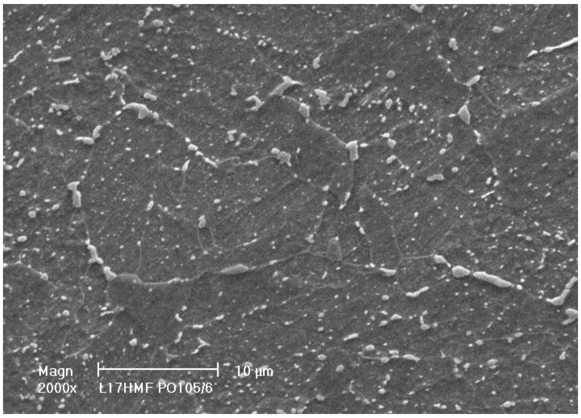
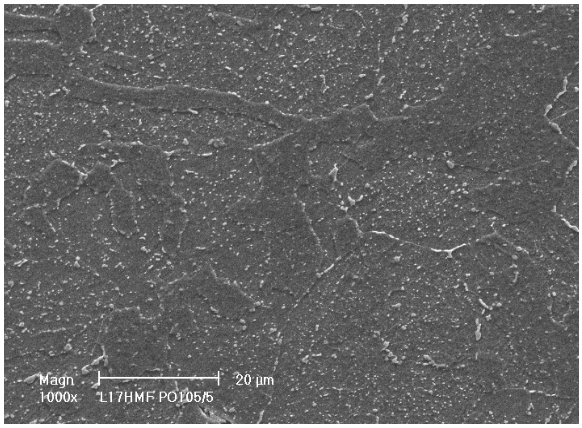


Fig. 7. Structure of G17CrMoV5-10 cast steel; after 105 000 hours of operation and creep test of 82 hours at the temp. 700ºC, SEM microsection, magnification a) 1000x, b) 2000x. Hardness 150 HV10

The structure of G17CrMoV5 - 10 (L17HMF) cast steel after creep test at the temperature of 680 and 700ºC and the test time of 226 and 82 hours, respectively, is a structure with numerous carbide precipitations and sparse bainite areas (Figs. 7, 8).It can be noticed that there is a slight increase of the precipitations size in comparison with the state after 105 000 hours of operation. Moreover, the precipitation chains on grain boundaries can be seen together with the coagulated carbide precipitates inside ferrite grains. Similar ferrite structures with numerous carbide precipitations of various sizes appearing on grain boundaries as precipitation "chains" were also observed after creep tests at the temperature of 620, 640 and 660^{o}C, and the time to rapture of 5485, 2066 and 864 hours, respectively (Figs. 9 - 11).

a)



b)

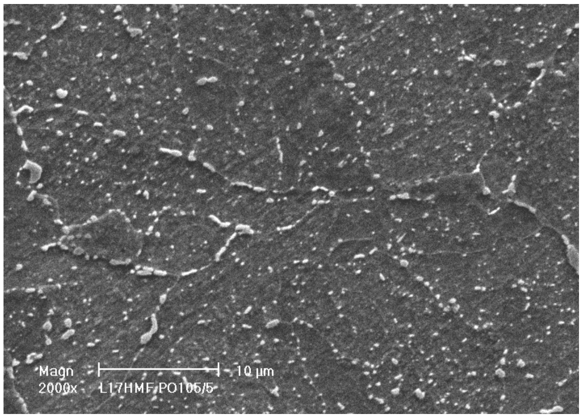


Fig. 8. Structure of G17CrMoV5-10 cast steel; after 105 000 hours of operation and creep test of 226 hours at 680ºC, SEM microsection, magnification: a) 1000x, b) 2000x. Hardness 151 HV10

3.4. X-ray analysis of phase composition of carbide isolates

During operation of ternary low alloy cast steels of Cr-Mo-V grade above the limit temperature T_g i.e. under creep conditions there are changes in the structure occurring, such as decay of bainite/pearlite accompanied by changes of grade, quantity, size and shape of carbides.

Therefore, occurrence of the particular carbide grades is connected with the extent of material life exhaustion. Qualitative phase analysis enables identification of the carbides isolated from the cast steel and assessment of their fraction.

Results of the analysis of precipitations phase composition for the T-pipe material after 105 000 hours of operation as well as the phase composition of carbide isolate in the form of an X-ray diffraction pattern is presented in Fig. 12.

Qualitative analysis of carbide precipitates was made on the basis of standard roentgenographic data from the database of the International Centre for Diffraction Data PDF-4.

a) b)

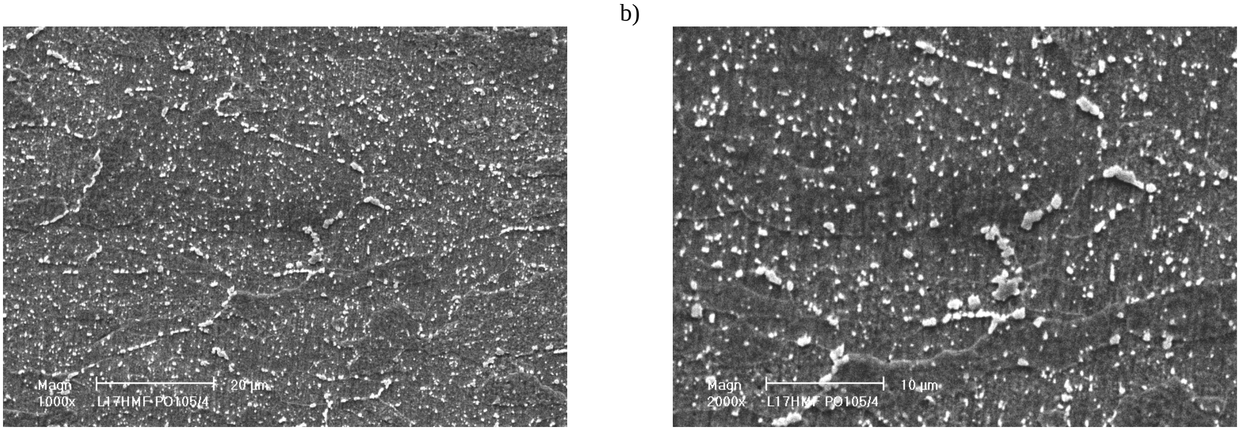


Fig. 9. Structure of G17CrMoV5-10 cast steel; after 105 000 hours of operation and creep test of 864 hours at 660ºC, SEM microsection, magnification a) 1000x, b) 2000x. Hardness 149 HV10

a) b)

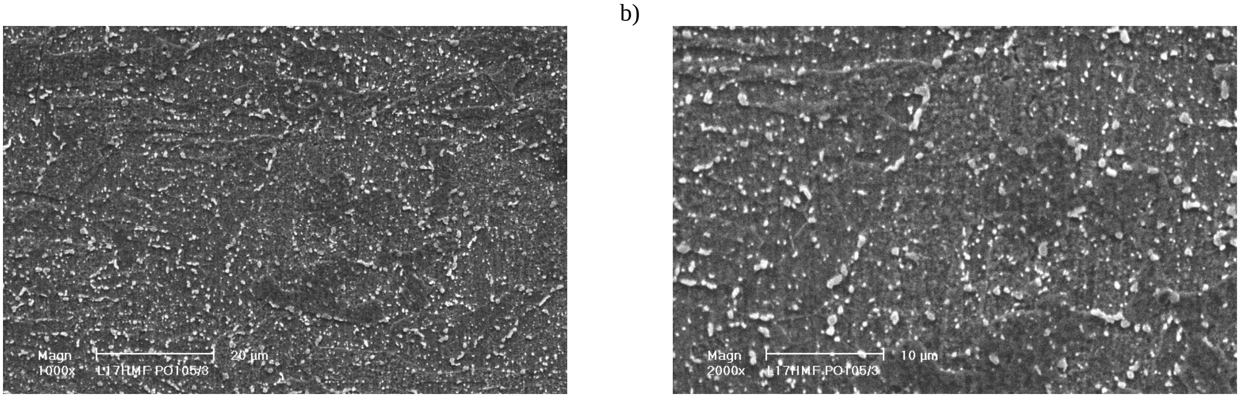


Fig. 10. Structure of G17CrMoV5-10 cast steel; after 105 000 hours of operation and creep test of 2066 hours at 640ºC, SEM microsection, magnification a) 1000x b) 2000x. Hardness 152 HV10

a) b)

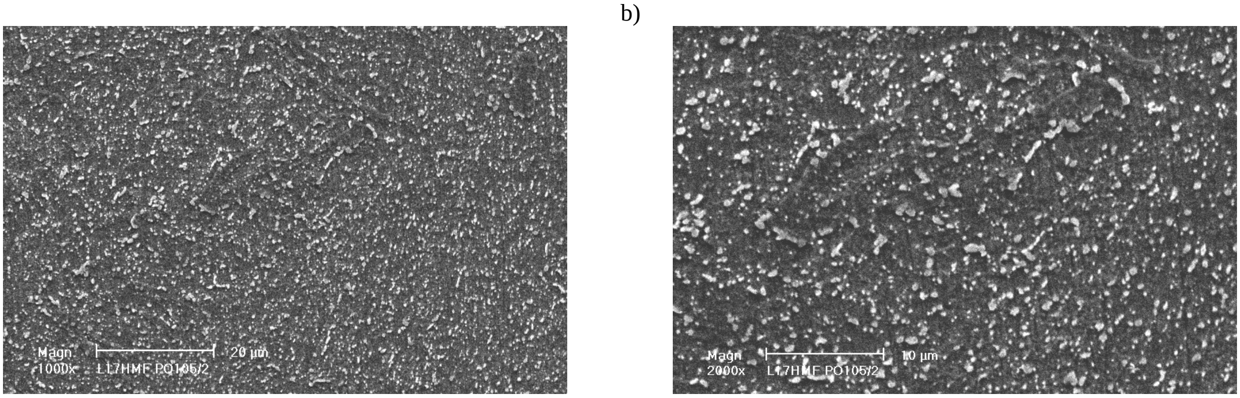


Fig. 11. Structure of G17CrMoV5-10 cast steel; after 105 000 hours of operation and creep test of 5485 hours at 620ºC, SEM microsection, magnification 1000x. Hardness 156 HV10, b) magnification 2000x. Hardness 156 HV10

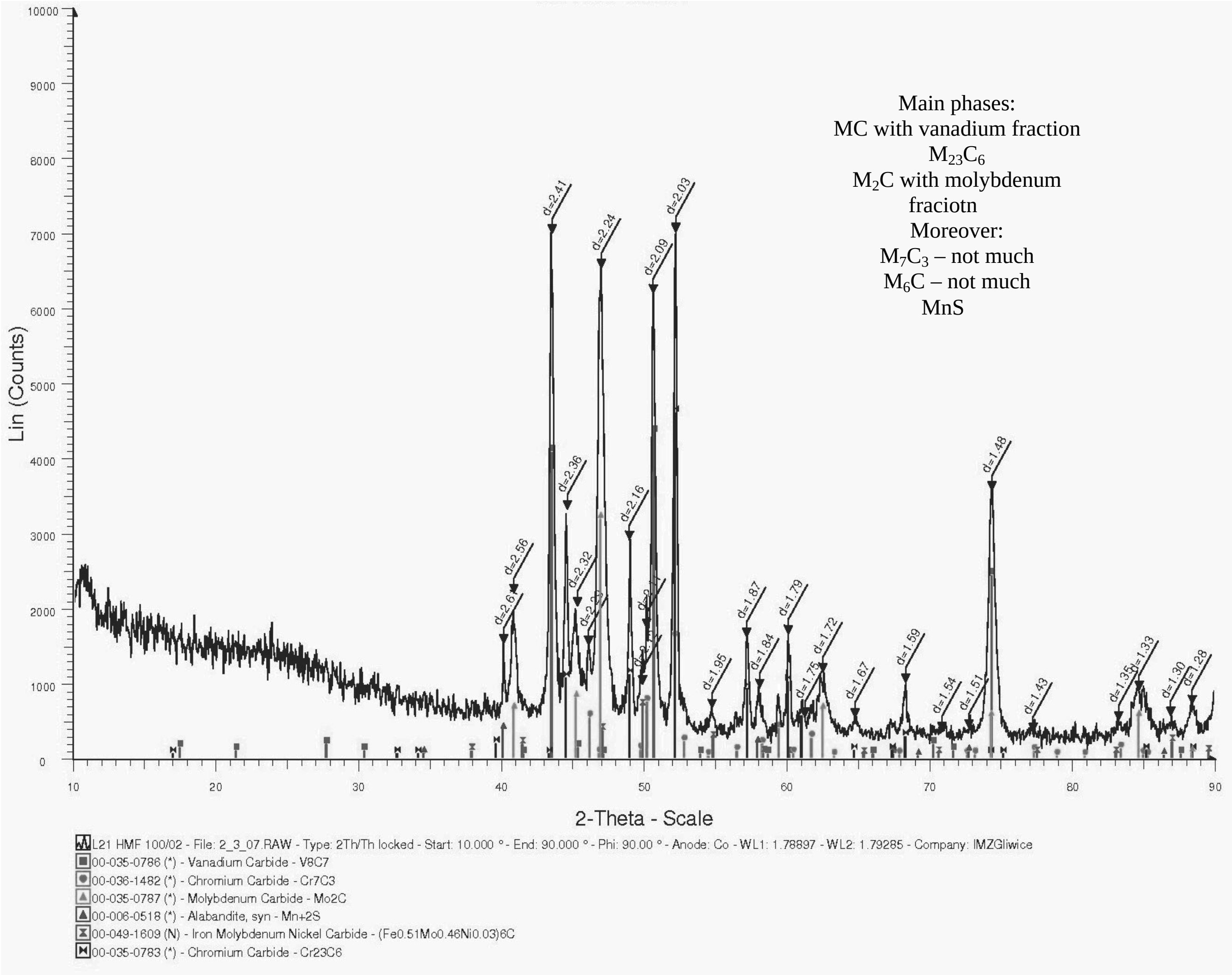


Fig. 12. X-ray phase analysis of precipitates in the G17CrMoV5-10 cast steel after 105 000 hours of operation

Diffraction pattern and the phase composition of carbide isolate is presented below.

4. Description of changes in the structure depending on the exhaustion extent

Performed structural research on the G17CrMoV5-10 cast steel materials after different operation time made it possible to work out a scheme of structure changes in relation to the extent of exhaustion which is going to be verified in the future (Fig. 13). Research on the phase composition of precipitations and literature data sources allowed to ascribe each particular state to the structure of sequence of how the carbide precipitation processes change.

5. Conclusions

1. Performed scientific research has confirmed a slight degradation of the examined T-pipe material made of G17CrMoV5-10 cast steel after 105 000 hours of operation under creep conditions. It can be proved by the following facts:

- the material meets the standard requirements concerning impact energy, tensile strength and yield point at room temperature;
- yield point determined at the temperature of 535 °C is comparable to the yield point required for 550 °C;
- determined DBTT temperature amounts to ca. +10 °C;
- it has been noticed that there is a slight degree of material exhaustion which according to internal IFM classification amounts to ca. 0.2-0.3.

2. Performed structural research of the G17CrMoV5-10 cast steel after 105 thousand hours of operation under creep conditions which has been subject to advanced creep tests at the temperature higher than the temperature of operation and under the test stress comparable to the operating stress, has proved that the research temperature has a significant influence on the extent of structure degradation and the time to rupture.
3. The advanced tests, applied to the T-pipe material after 105 000 hours of operation, carried out under constant stress corresponding to the operational one, enabled determining of the disposable residual life for operating parameters of work during further operation. For the assumed operating stress of 60 MPa and the temperature of 535°C, the disposable residual life amounts to ca. 275 000 hours.
4. Obtained results of the structural research on the G17CrMoV5-10 cast steel after 105 000 hours of operation and after the applied creep tests, have made it possible to create a scheme of changes in the structure image together with the state of development of the carbide precipitation processes, corresponding to those changes, and compared to the extent of the serviced material's life exhaustion. Along with the materials characteristics after operation, it is used for the condition assessment of steel cast elements serviced under creep conditions.

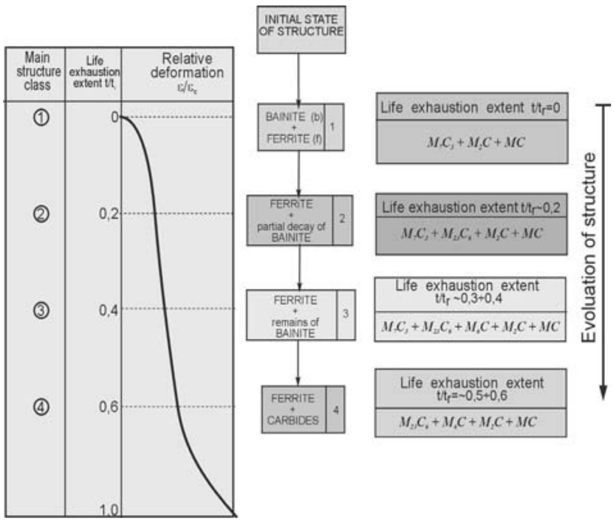


Fig. 13. Diagram of changes in the microstructure image in relation to the extent of life exhaustion for the G17CrMoV5-10 cast steel operating under creep conditions

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