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Mechanical properties and structure of the Cr-Mo-V low-alloyed steel after long-term service in creep condition

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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 Cr-Mo-V low-alloyed steel.
Design/methodology/approach: The investigated material has been obtained from the Polish power stations. All examined elements have exceeded their assessed life of 100 000 hours. Mechanical properties and structure examinations were carried out on materials after long-term service in creep conditions. The microstructure have been observed using a light and a scanning electron microscope. The investigation of the development of the precipitation processes were done by X-ray diffraction phase analysis.
Findings: Carbide precipitations evolution in correlation to the life exhaustion extent were presented. Residual life in creep short tests was done. Residual life in correlation to changes structure and developed of carbide precipitation processes were presented.
Practical implications: The presented methods can be used for materials evaluation operating in creep conditions.
Originality/value: The presented results changes in the mechanical properties, structure and in the precipitation processes are applied to evaluation of the condition of the elements in further industrial service.
Keywords: Mechanical properties; Structure; Phase analysis; Degradation after creep service; Residual life

1. Introduction

Institute for Ferrous Metallurgy carries out since many years research and services for the power industry and heat engineering referring to assessment of material state and critical elements of the high-pressure equipment in creep service. These elements have exceeded most often significantly their design service time being most often 100.000 hours long. They require forecasting their further safe service for the operating conditions. Carrying out such assessment calls for employment of a number of proven diagnostic methods. Assessment methods of materials state in service also belong to these methods, and assessment of material is one of the most significant factors in assessment of the state of the examined elements [1÷3]. Material specifications are required to carry out such assessment and not only those of the general use steel products but also of materials after the long time service, especially in creep conditions [1,6,7]. Apart from such characteristics, knowledge is needed of structure changes occurring during its degradation connected with the decay of its main components, development of the precipitation processes and processes of internal defects [5÷16].

Investigation results presented below feature a fragment of the successive stage of solving these problems for the 0.5Cr-0.5Mo-0.25V low-alloy steel from which live steam pipelines in creep service are mostly made.

2. Materials for investigation

Investigations were carried out on the 0.5Cr-0.5Mo-0.25V (13HMF) type low-alloy steel after various creep service time

Table 1.
Material for investigation - chemical compositions of the examined materials from the 0.5Cr-0.5Mo-0.25V low-alloy steel after service

Service time t_e, [h]	Chemical composition [%]										
	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al
105 000	0.12	0.55	0.24	0.022	0.025	0.45	0.098	0.64	0.32	0.051	0.008
118 000	0.11	0.57	0.26	0.021	0.018	0.46	0.14	0.67	0.36	0.084	0.006
133 000	0.15	0.49	0.29	0.025	0.012	0.6	0.04	0.59	0.26	0.016	<0.005
148 000	0.15	0.55	0.26	0.020	0.004	0.40	0.083	0.66	0.34	0.087	0.027
164 000	0.12	0.49	0.36	0.016	0.014	0.58	0.16	0.30	0.20	0.11	0.008
PN-75/H-84024	0.10-0.18	0.40-0.70	0.15-0.35	max. 0.04	max. 0.04	0.30-0.60	max. 0.30	0.05-0.65	0.22-0.35	max. 0.25	max. 0.02

Table 2.
Material for investigation - service parameters and types of the investigated elements

No	Service time [h]	Service parameters		Element type Dimensions [mm]
		Design pressure p_o [MPa]	Design temperature T_o [°C]	
1	105 000	14.0	540	Live steam pipeline ϕ 273x32
2	118 000	14.0	540	Live steam pipeline ϕ 273x32
3	133 000	18.7	548	Live steam pipeline ϕ 508x70
4	148 000	14.0	540	Live steam pipeline ϕ 273x32
5	164 000	13.95	540	Live steam pipeline ϕ 323.9x40

periods from about 105,000÷200,000 hours. Material for investigation featured sections of the main live steam pipelines of the pressure part of the power boilers. Chemical compositions of materials being elements of the pipelines, compared to the requirements, are presented in Table 1. On the other hand, service time and design parameters of the investigated sections are shown in Table 2.

3. Mechanical properties and structure after long term creep service

3.1. Mechanical properties

Examination of mechanical properties was carried as tensile tests at room temperature and the following parameters were determined: ultimate tensile strength UTS, yield point YP, as well as elongation TEI, and moreover the yield point YPt at the elevated temperature, with the values close to the service one. Results of these examinations give base to the statement that the investigated materials meet the requirements of the relevant standards for the steel products in the area of the above mentioned strength coefficients. No correlation was observed between the investigated strength coefficients and creep properties of materials after long time creep service. This correlation does not occur for materials in the state as delivered from the steel plant either. An attempt to employ the impact strength tests of the test pieces with the V-notch carried out at various test temperatures was made to determine usefulness of the material after the long time service. Compared to the initial state the fracture appearance transition temperature for all materials of the investigated elements from the 0.5Cr-0.5Mo-0.25V low-alloy steel is shifted towards their higher values. Moreover, most of the investigated materials after creep service are characteristic of the lower impact strength than the minimum one required from the material as delivered from the steel plant. It was found out that the impact strength value depends mostly on development of the precipitation processes and also on development of the internal damages and structure discontinuities originated during the service. However, impact tests cannot be used for assessment of the further safe service time. Therefore, it is not useful for the residual life assessment and for determining of the exhaustion extent. However, it is indispensable for assessing the material's deformability and its capability to carry the load connected with the pressure tests, as well as in limiting the number of banking and setting to work the installation in its further service process. Investigation results confirming the shift of the fracture appearance transition temperature from about -40°C to even +50°C for materials with the significant structure degradation and advanced development of the precipitation processes are shown in Fig. 1.

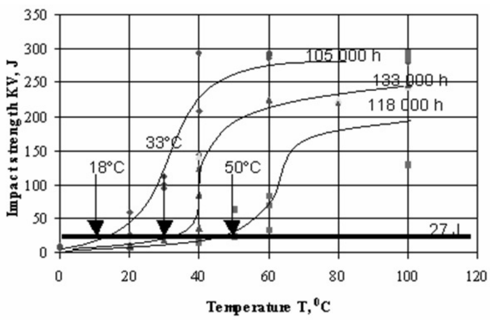

Fig. 1. Shift of the fracture appearance transition temperature due to the long time creep service of the 0.5Cr-0.5Mo-0.25V low-alloy steel

3.2. Creep resistance

The abridged creep tests were used in the creep resistance examinations carried out [3]. Cutting the creep test time was obtained by increasing the test temperature T_b compared to the service temperature T_r, however, at the constant test stress value σ_b corresponding to the service one σ_r (σ_b=σ_r). Test results for the 0.5Cr-0.5Mo-0.25V (13HMF) low-alloy steel after the various service time periods t_e much longer than the design service time t_o of 100,000 hours are presented in Fig. 2 as the relationship log $t_r = f(T_b)$ for $\sigma_b=\sigma_r$=60MP.

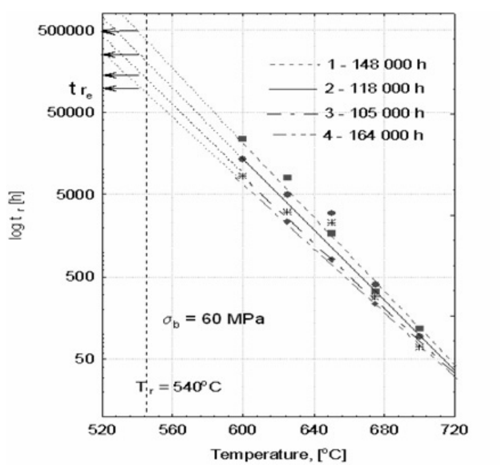

Fig.2. Abridged creep tests results of the 0.5Cr-0.5Mo-0.25V low-alloy steel at the constant test stress corresponding to the service one $\sigma_b=\sigma_r$= 60MPa

Table 3.
Determining the residual life based on the abridged creep tests

Parameters of further service		Creep test parameters		Service time t_e, [h]	Residual life t_{re}, [h]
Temperature T_o, [°C]	Stress σ_o, [Mpa]	Temperature T_b, [°C]	Stress σ_b, [MPa]		
540	60	540	60	148 000	~500 000
				118 000	~313 000
				105 000	~150 000
				164 000	~143 000

Based on the test results the residual life t_{re} was evaluated by extrapolation for the investigated materials, which is marked in Fig. **2**. It is the time to rupture of the material after its long time service for the assumed common service temperature t_r=540°C.
The residual life t_{re} values obtained are listed in Table 3 along with the phase compositions of the carbides obtained with the X-ray phase analysis of the isolates, and with the service time t_e, as well as the design temperature T_o determined by the designers.
These results are a sign of the direct relationship between the residual life t_{re} and the development extent of the precipitation processes of carbides, which results from their phase composition and portions of the particular precipitation types.

3.3. Structure

Metallographic examinations of various steel grades after creep service revealed that transformations of carbides and morphological changes of phases have the most significant effect on service properties degradation. The type of the main phase and proportions of the other carbides in the structure decide creep resistance of the material after service [1,5÷7]. Creep tests of the investigated 0.5Cr-0.5Mo-0.25V steel after service, of the materials with no internal defects caused by creep, confirmed the existence of relationships between the phase compositions of carbides and the residual life. Microstructure examinations were carried out on the scanning- and transmission electron microscopes. The initial state structure of the 0.5Cr-0.5Mo-0.25V low-alloy steel features the mixture of bainite with ferrite, sometimes with a small amount of pearlite. Occurrences of the significant amount of the M_3C carbides and numerous, very fine MC type ones, are identified in such material. The first stage of the structure changes is characteristic of the slight decay of the bainite (pearlite) areas. This is accompanied by coagulation of precipitations in these areas. This is the first stage of the bainite (pearlite) areas decay. The coagulation process of carbides insi de of the bainite areas is accompanied by precipitation of carbides on the ferrite grains boundaries. The long lasting simultaneous action of temperature and stress causes dissolving of one carbide type with the simultaneous origination of another carbide type or development of new carbides by the in situ transformation. In this way the amount of the current carbides is reduced and origination of new ones of another type takes place. The significant decay of the bainite (pearlite) areas due to the long term creep is the next stage of structure changes. The coagulated precipitations of varying size, some of them quite big, are observed inside of these areas On the other hand, on the ferrite grains boundaries precipitations occur forming chains. The final structure image is ferrite with rather homogeneously distributed precipitations inside grains and chains of the significant amount of precipitations on their boundaries. The main phase component of material precipitations in such state is the M_6C carbide occurring along with the $M_{23}C_6$ and MC ones and sometimes with the scant amount of other types of carbides.

4. Effect of structure changes and state of the carbides' precipitation processes development on residual life

The obtained creep resistance results in the abridged creep tests for the investigated materials from the 0.5Cr-0.5Mo-0.25V type low-alloy steel after the long term creep service were arranged depending on their residual life t_{re} value and its corresponding exhaustion extent, defined as the ratio of the service time t_e to the total forecasted time to damage t_r. Based on the structural examination results the particular structure classes were attributed to the particular examined materials, and the carbides phase composition was determined based on the X-ray phase analysis of the carbides isolates, which are presented in Table 4.Analysis of the obtained results carried out revealed existence of the direct connection among the structure image, development of the precipitation processes, residual life, and exhaustion extent defined as the ratio of the service time t_e to the total forecasted time to damage t_r [2,3]. The smaller the residual life t_{re} is, the more advanced decay of bainite areas is, more advanced is development of the carbides precipitation process, higher structure class, and exhaustion extent. Based on the investigation results presented above and investigations of other materials from the 0.5Cr-0.5Mo-0.25V type steel after various service periods of up to 200,000 hours the schema was worked out of structure changes during the long term creep service of this steel in connection with the exhaustion coefficient and relative strain. Sequence of carbides changes of the investigated steel was worked out based on this research, It will be presented in another publication.

Table 4.
Residual life, its corresponding carbides phase composition, and exhaustion extent of the 0.5Cr-0.5Mo-0.25V type low-alloy steel (T_b= 540°C; σ_b=60MPa)

Service time t_e, [h]	Residual life t_{re}, [h]	Phase composition of precipitations 1.)	Exhaustion extent t_e/t_r	Structure class 2.)
148 000	~500 000	$MC_{f.g..}$ $+Fe3C_{f.g.}$$+M23C6_{m.}$$+M6C_{m.}$	0.23	1
118 000	~313 000	$MC_{d.}$ $+M2C_{d.}$$+M23C6_{m}$ $+M6C_{m.}$	0.27	1/2
105 000	~150 000	$MC_{f.g..}$ + $M2C_{ś.}$$+M23C6_{m.}$	0.41	2
164 000	~143 000	$M23C6_{d.}$+ $MC_{d..}$$+M7C3_{m.}$ + $M2C_{m.}$	0.58	2/3

1.) f.g. – main component; d – much; ś - average; m - little
2.) According to the internal classification of the Institute for Ferrous Metallurgy for the 13HMF (14MoV63) steel

5. Conclusions

1. No correlation was observed between the investigated strength coefficients and creep properties of materials after long time creep service. This correlation is not observed either for the investigated 0.5Cr-0.5M0-0.25V type low-alloy steel in the initial state.
2. Long term service, and especially its resulting development of the precipitation processes of carbides, as well as development of the internal defects due to creep, cause shift of the fracture appearance temperature into the positive temperature direction. The fracture appearance temperature may exceed even +50°C. Its knowledge it is indispensable for assessing the material's deformability and its capability to carry the load connected with the pressure tests, as well as in limiting the number of banking and setting to work the installation in its further service process.
3. The microstructure changes of the 0.5Cr-0.5Mo-0.25V type low-alloy steel due to the long term creep service are connected with decay of bainite (pearlite), development of the carbides precipitation processes, and in its final stage, with development of the internal defects.
4. The direct connection was revealed among the microstructure image, development stage of the precipitation processes, residual life, and exhaustion extent of the investigated steel in creep service. The smaller the residual life is, the more advanced decay of bainite areas is, more advanced is development of the carbides precipitation process, higher structure class, and exhaustion extent.

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