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DEGRADATION OF MECHANICAL PROPERTIES OF CrMo CREEP RESISTANT STEEL OPERATING UNDER CONDITIONS OF CREEP

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Preliminary Note – Prethodno priopćenje

Mechanical properties of a steam tube made of CrMo creep resistant steel are analysed in this contribution after up to $2{,}6 \cdot 10^5$ hours service life in creep conditions at temperature 530 °C and calculated stress level in the tube wall 46,5 MPa. During service life there were in the steel gradual micro structure changes, first pearlite spheroidization, precipitation, coagulation and precipitate coarsening. Nevertheless the strength and deformation properties of the steel (R_e, R_m, A_5, Z), and the resistance to brittle fracture and the creep strength limit, were near to unchanged after $2{,}1 \cdot 10^5$ hours in service. The steam tube is now in service more than $2{,}6 \cdot 10^5$ h.

Key words: mechanical properties, creep resistant steel, creep properties, degradation

Degradacija mehaničkih svojstava na puzanje otpornog CrMo čelika rabljenog pri uvjetima puzanja. Članak analizira mehanička svojstva paravode izrađenog iz CrMo vatrootpornog čelika poslije rabljenja do $2{,}6 \cdot 10^5$ sati pri uvjetima puzanja pri temperaturi 530 °C i praračunato naprezanje u stjenci cijevi 46,5 MPa. Tijekom rabljenja postupno je dolazilo u ispitivanom čeliku do strukturnih promjena prvenstveno sferoidizaciji perlita, precipitaciji, koagulaciji i okrupnjavanjem precipitata. Usprkos navedenim promjenama čvrstoća i deformacijska svojstva (R_e, R_m, A_5, Z) otpornost krhkom lomu i puzanju i pri rabljenju do $2{,}1 \cdot 10^5$ sati praktički se nisu izmjenili, a parovod je u upotrebi čak $2{,}6 \cdot 10^5$ sati.

Ključne riječi: mehanička svojstva, čelik otporan na puzanje, svojstva puzanja, degradacija

INTRODUCTION

During service life in creep conditions there is a gradual micro structure degradation of steel and this way some decrease of properties. Coagulation and coarsening of precipitates, carbides transformation, additional precipitation, and the evacuation of alloying elements from the matrix, are supposed to be the most detrimental processes [1-5]. Embrittlement, weakening of the micro structure and the final creep failure can be the result. The degree and intensity of creep degradation depend on both, in service conditions (temperature, stress, environment) and exposition time [2, 3, 6-8].

It is very important to study and know the time dependence of the performance of steel in service conditions and this way survey the possibilities of service life increase.

The aim of this contribution is to consider the extent of micro structure degradation, the influence on mechanical and brittle fracture properties and first of all on creep strength limit for the tested CrMo creep resistant steel for service life up to $2{,}6 \cdot 10^5$ h in given conditions.

MATERIAL AND METHODS

The experimental material was cut out from pieces of the steam tube Ø 335,6 × 41 mm. The tube was in service at temperature 530 °C and calculated stress level in the tube wall 46,5 MPa for exposition times $1{,}02 \cdot 10^5$ h, $1{,}57 \cdot 10^5$ h, and $2{,}21 \cdot 10^5$ h. The steam tube was made of CrMo creep resistant steel (10CrMo9.10). The chemical composition of the tested steel is in Table 1.

Table 1 **Chemical composition of the tested steel /%**

Material	C	Mn	Si	Cr	Mo	V
CrMo Steel	0,11 0,13	0,46 0,48	0,24 0,27	2,06 2,19	0,96 1,02	0,005 0,02

Ranges of chemistry are given in Table 1. The different cut outs were from different parts of the steam tube showing slight differences in element contents.

From the tested steel tube test samples were machined in longitudinal direction for tensile tests, creep strength limit tests, hardness tests, Charpy impact tests, and polished surfaces for micro structure evaluation.

Universal tensile test machine INSTRON 1185 was used for static tensile tests. For impact tests V notch test pieces with dimensions 10 × 10 × 55 mm were used and tested on a PSW 3000 pendulum Charpy impact tester in the temperature range from +100 °C to -40 °C. Hardness HV was measured by the Vickers method. Creep

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strength limit was determined by creep tests at 530 °C. The stress values for the test were calculated to end tests with time to fracture in the range from 10^3 to 10^5 h. Experimental time to fracture results were in the range from 5.10^2 to 5.10^4 hours.

After service life $2{,}5\cdot10^5$ and $2{,}6\cdot10^5$ h samples were cut out from the critical place in the steam tube. The shape of the cut outs was a spherical cap 0,6 mm high and Ø 8 mm in diameter. The samples were tested for changes in the micro structure, micro hardness HV0,05 and by a „Small Punch Test – (SPT)“, the last one giving yield point R_e, and ultimate tensile strength R_m values [8,9].

Micro structure was analysed in polished surfaces from the original material as well as on the samples cut out after the listed service life times by light microscope OLYMPUS and electron microscope JEOL JSM 7000 F.

RESULTS AND DISCUSSION

The tensile test results, and hardness test results HV for the original material and after service life at temperature 530 °C and stress level 46,5 MPa are plotted in Figure 1 and Figure 2.

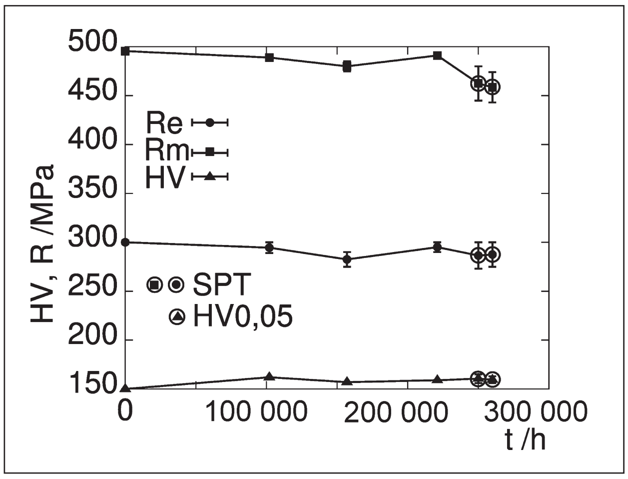

Figure 1 Influence of service life t on yield point $R_{e,}$ strength R_m and hardness HV. Service conditions 530 °C and stress level 46,5 MPa

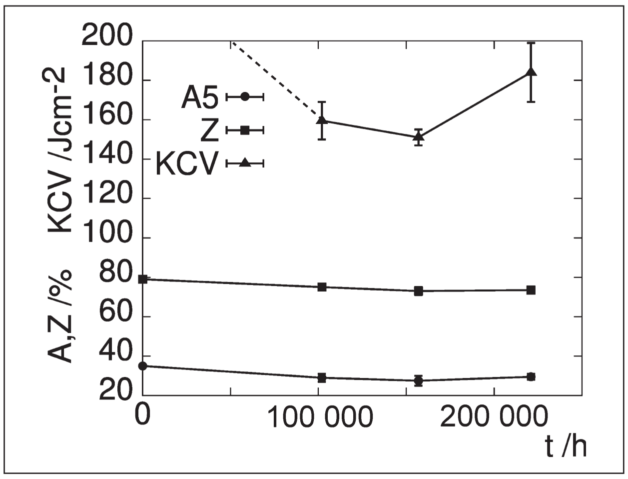

Figure 2 Influence of service life t on ductility A, reduction of area Z and impact energy KCV. Service conditions 530 °C and stress level 46,5 MPa

As results showed after service life as long as $2{,}6\cdot10^5$ h no significant degradation of mechanical properties (R_e, R_m, A_5, Z), hardness HV (HV0,05), and impact energy KCV was observed Figure 2.

A slight decrease of impact energy was observed between the initial state (KCV = 250 Jcm^{-2}) and the value after service life $1{,}02\cdot10^5$ h. A slight decrease of R_e, and R_m about 5 % and the increase of hardness HV about 6 % after service life $1{,}57\cdot10^5$ h can be explained by the small deviation in chemical composition (Table 1), or to changes in micro structure, which progress in every steel in creep conditions. The wider scatter in R_e, R_m and HV0,05 values for tests after service life times $2{,}5\cdot10^5$ h and $2{,}6\cdot10^5$ h, are contributed to the fact, that the values were measured by SPT in mini samples, and not by the standard test methods. The mini samples are more sensitive to the influences of micro structure heterogeneity.

The tested steel showed high ductility A_5 and reduction of area Z values. After service life time $2{,}21\cdot10^5$ h the plastic properties decreased about 6 %, only. Charpy impact energy, the test most sensitive to changes in the micro structure, was not changed significantly after service life times from $1{,}02\cdot10^5$ up to $2{,}21\cdot10^5$ hours. The impact energy was high and satisfactory even after $2{,}21\cdot10^5$ hours in service. There are important values to define the resistance to brittle fracture and they are the transition temperature T35 – temperature with the limit value of KCV = 35 Jcm^{-2}, or the transition temperature T50% - temperature limit for the 50 % ductile fracture in the fracture surface of broken impact test samples.

In Table 2 are the determined transition temperatures for the tested steel for initial state as well as after the listed service life times.

Table 2 **Transition temperatures of the tested steel after in service times**

Time /h	$1{,}02\cdot10^5$	$1{,}57\cdot10^5$	$2{,}21\cdot10^5$
T35 /°C	-7	-17	-8
T50 /°C	+5	+6	+1

As it can be seen in Table 2, the resistance to brittle fracture did not change significantly with the service life. Such transition temperatures warrant resistance to brittle fracture from room temperatures at layoffs, through the start up, all over to the highest operating temperature and full load.

The experimental test results showed that the mechanical and brittle fracture properties after $2{,}6\cdot10^5$ h in service are still higher than the limit values requested by the standard for the used CrMo steel grade (R_{emin} = 265 MPa, R_{mmin} = 440 MPa, $A_5 > 20$ %, KCU 3 > 69 J·cm^{-2}).

For the steam tube design the most important value for the load bearing calculation is the creep strength limit R_{Tm}.

In Table 3 are the determined creep strength limit values R_{Tm} for the tested steel for initial state as well as after the listed service life times.

Table 3 **Creep strength limit R_{Tm} at 530 °C initial state and in service life time for tested CrMo steel**

Service life / h x 10^5	0	1,02	1,57	2,21
$R_{Tm}10^4/530$	128	120	121	128
$R_{Tm}10^5/530$	86	81	81	84
$R_{Tm}2,2.10^5/530$	74	70	70	71

Test results confirmed that the creep strength limit values did not change significantly with the service life time, and they are in good agreement with strength data form tensile tests (Figure 1).

The creep strength limit decrease was in the range from 3 to 6 %. During service life there were in the steel gradual micro structure changes (degradation of the initial micro structure). It was confirmed by the micro structure analyses of the tested steel. In Figure 3 to Figure 6 are documented the micro structures starting from the initial state up to service life times $1{,}02\cdot10^5$ h, $1{,}57\cdot10^5$ h and $2{,}6\cdot10^5$ h.

Based on metallography a conclusion can be made: The initial micro structure is ferrite-pearlite, in condition after normalization annealing and tempering (Figure 3). After this annealing and tempering the pearlite is spheroidized, making the microstructure more stable.

After $1{,}02\cdot10^5$ h in service, the micro structure has changed. It is still ferrite-pearlite, but by the long time exposition to high temperature the pearlite was spheroidized more (Figure 4).

Pearlite spheroidization continued with the growth of service life time. For $1{,}57\cdot10^5$ h exposition the pearlite was completely spheroidized (Figure 5).

Micro hardness in the pearlite grains was HV0,05 = 168 and in ferrite HV0,05 = 157. The process heading towards the equilibrium state continued and the micro structure had changed to a ferrite-carbide mixture. In the ferrite matrix there were only scattered carbides after $2{,}6\cdot10^5$ h, as documented in Figure 6. In grain boundaries coarse carbide particles were segregated, forming net like patterns in some localities.

A more detailed micro structure and phase analysis was completed by the means of electron microscopy (TEM and REM).

The results showed during the long time exposition in service in creep conditions gradual micro structure degradation of the tested steel. Pearlite decomposition, secondary precipitation, coagulation and coarsening of particles, changes in the chemical composition of carbide particles, the last ones based first on (Fe,Cr,Mo)C and depletion of alloying elements from the matrix were

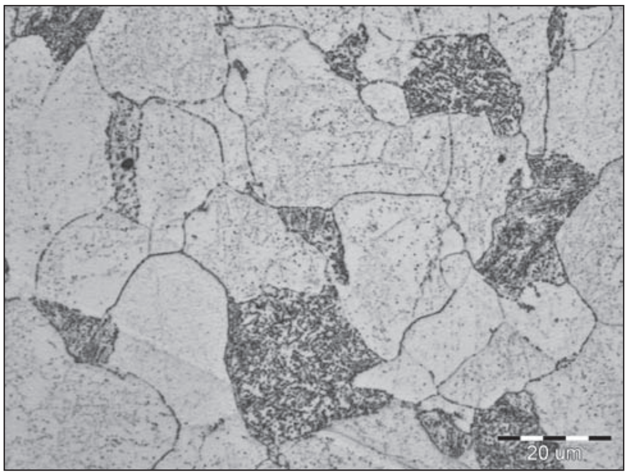

Figure 3 Microstructure of tested steel – initial state

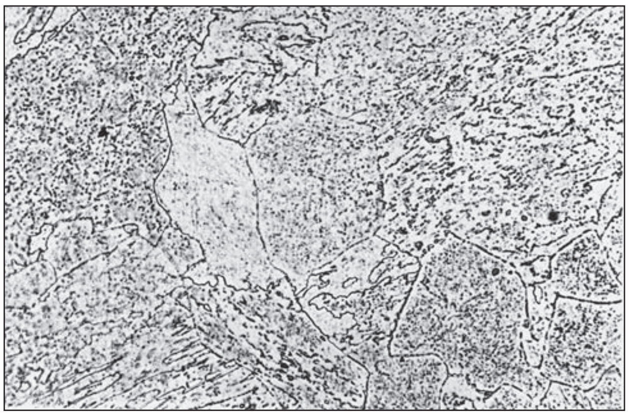

Figure 4 Microstructure of tested steel after $1{,}02\cdot10^5$ h in service, magn. 400x

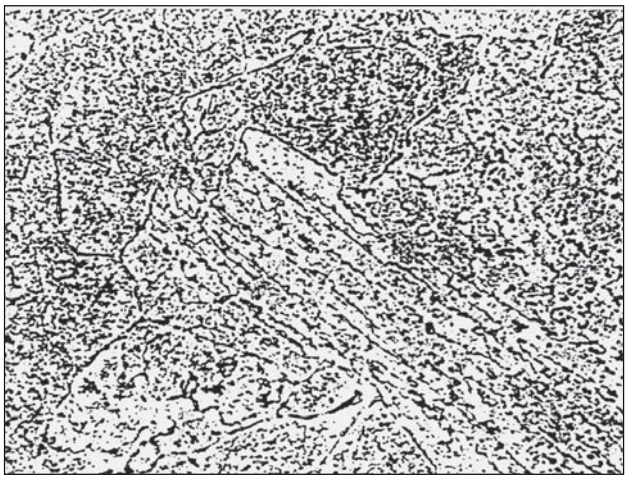

Figure 5 Microstructure of tested steel after $1{,}57\cdot10^5$ h in service, magn. 800x

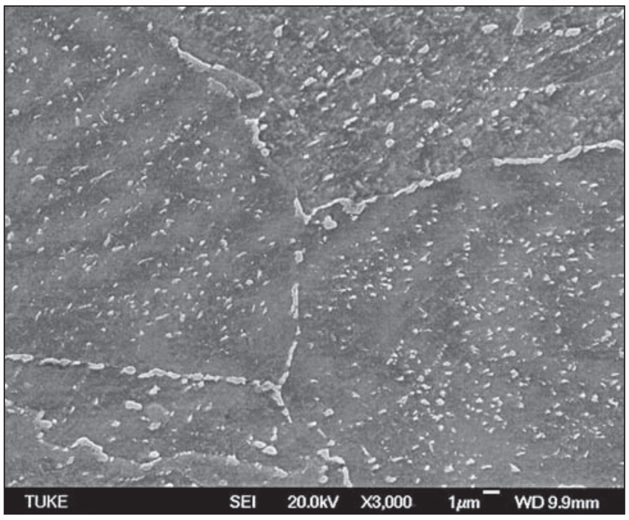

Figure 6 Microstructure of tested steel after $2{,}6\cdot10^5$ h in service

observed. Extremely important: electron microscopy had not given any sign of creep crack initiations.

The experiments confirmed changes of microstructure in the creep resistant CrMo steel at 530 °C and stress 46,5 MPa in service during $2{,}6 \cdot 10^5$ h. However, there were neither significant changes in common mechanical properties nor that of the creep strength limit. It is confirmed, too, by the known dependence of the creep strength limit R_{Tm} on the yield point R_e. As results showed the yield point changed a little only after $2{,}2 \cdot 10^5$ h or $2{,}6 \cdot 10^5$ h, also a slight change could be supposed for the $R_{Tm}10^5/530$. It was confirmed by the experiments.

The yield point R_e can be considered to be the macro characteristic of the micro structure. The relation between R_e and the micro structure can be described by parametric equations [1,10]. Changes of micro structure during service in creep conditions are changing the contributions of precipitation and dislocation strengthening, what is decisive for the value of R_e. As described in work [1] the R_e value decreased about 14 % due to the decrease first of dislocation strengthening about 11 % and precipitation strengthening about 9 %, in a CrMo steel after 10^5 h at 540 °C. In work [7] is reported a decrease of the R_e by the exposition $2{,}65 \cdot 10^5$ h at 540 °C and stress level 44,8 MPa as high as 26 %.

On the other hand in our experiments as is shown in Figure 1 experimental results confirmed a less decisive decrease of the yield point mean values R_e (about 5 %) and little more of ultimate tensile stress R_m (about 8 %) after $2{,}2 \cdot 10^5$ h at 530 °C. It is in close correlation to the extent of coaugulation and coarsening of dispersed phases. In proportion to that it was possible to suppose the decrease of the value of R_{Tm} after $2{,}2 \cdot 10^5$ h in service.

The system of safe work and the safe service life of the power plant are warranted by safety coefficients “n” of the parts used in given service conditions. Our safety coefficient was calculated by the following equation:

$$n = (R_{Tm}10^5/530)/R_N = 86/46{,}5 = 1{,}85$$

where $R_{Tm}10^5/530$ is the creep strength limit of the initial state for the planned service life 10^5 h at 530 °C, and R_N is the calculated stress level. Supposing the validity of the discussed correlation between R_e and R_{Tm} a prediction can be made for the service life $2{,}6 \cdot 10^5$ h:

$$R_{Tm}10^5/530 = 80{,}8 \text{ MPa} \quad \text{and} \quad n = 1{,}74.$$

Taking into account the experimental results and the described analysis it has been recommended to continue the power plant operation up to $2{,}8 \cdot 10^5$ h.

CONCLUSION

The aim of this contribution was experimental service life verification and safety analysis of a CrMo steel grade steam tube in creep conditions. Influence of service conditions on properties was evaluated. The steam tube working at high temperature 530 ºC and stress level in the tube wall 46,5 MPa was tested after service life times $1{,}01 \cdot 10^5$, $1{,}57 \cdot 10^5$, $2{,}21 \cdot 10^5$, $2{,}5 \cdot 10^5$ and $2{,}6 \cdot 10^5$ h. The following has been shown by the experiments and analyses:

- Changes in the micro structure were induced in the steel by the long time operation in the given conditions. The initial ferrite – pearlite micro structure was gradually transformed into ferrite - carbides mixture during operation, with the gradual carbide particles coaugulation and coarsening.
- Up to the service life time $2{,}6 \cdot 10^5$ h no creep crack initiations were observed by electron microscopy. In consequence, even after this time of operation the creep is in the second predictable linear stage.
- Changes in the following mechanical and creep properties were not significant after $2{,}21 \cdot 10^5$ h in service: yield point, ultimate tensile strength, ductility, reduction of area, and creep strength limit $R_{Tm}10^4/530$, and $R_{Tm}10^5/530$.
- Larger scatter of mechanical properties was measured after $2{,}5 \cdot 10^5$ and $2{,}6 \cdot 10^5$ h in service. It is supposed, due to the change in the test method. The decrease of mechanical properties in comparison to the initial state is still convenient, not large. (R_e about 5 %, R_m about 8 %, and HV down about 15 %).
- Consequently, if regular inspection tests are applied, with the variety of tests and analyses described, it is possible to learn more about service conditions and guarantee safe service life continuation exceeding the usual calculated or planned service life. Though it means expenses, for sure it pays back, either by avoiding unexpected break down damages, or by the profit of extended safe service life continuation.

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