LIFE ASSESSMENT OF HIGH PRESSURE STEAM PIPING BEND WORKING UNDER CONDITIONS OF CREEP DAMAGE

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Abstract

For many years, low alloy CrMo(V) creep-resistant steels are applied for parts in the construction of energy and chemical structural units working under creep conditions (temperature about 550 °C and pressure about 15 MPa). These steels most often include creep-resistant steel 13CrMo4-4 (ČSN 15 121), 14MoV6-3 (ČSN 15 128), 10CrMo9-10 (ČSN 15 128). The main problem of steam pipe-lines made of these creep-resistant steels is a residual lifetime, because these parts are at presence in most Czech power plants at the end of their designed lifetime (2,5 . 10^5 hours).

This article deals with a lifetime assessment of one steam piping bend made of ČSN steel 15 128 (14MoV6-3) which was operated in conditions of creep damage in Czech fossil fuel power plant until its creep deformation obtained a limit of 1 percent. The overall condition of the bend was assessed using replica and cross section metallography including electron microscopy and by evaluation of mechanical properties in as-received state and after additional laboratory ageing at 600 °C for up to 5 000 hours in air conditions. As the final result, the residual lifetime by using mathematical approaches and standards was estimated.

Keywords: Low alloy creep-resistant steels, creep, life assessment of steam pipe-lines, microstructure rating charts, laboratory ageing

1. TEST EXPERIMENTAL MATERIAL

1.1. Steel 15 128 (14MoV6-3)

15 128 steel (14MoV6-3) is low alloyed CrMoV creep-resistant steel with guaranteed weldability. It is used for long-term components of power equipment operating under elevated pressure up to temperature 580 °C. Creep resistant of this steel is obtained by precipitation hardening of globular carbides dispersed phases of V_4C_3 type, excluded in the ferritic matrix, and globular carbides of $M_{23}C_6$ type excluded at the grain boundaries. The initial microstructure of the steel in the initial state depends on heat treatment and in this case of 15 128.5 steel, the microstructure is ferritic-bainitic. The chemical composition of the steel according to [1] and according to a comparative measurement on cross-section samples by using optical emission spectrometer is shown in **Table 1**.

Table 1 The chemical composition of the steel 15 128 (14MoV6-3)

Element	C	Si	Mn	Cr	Mo	V	P	S	Al
According to [1]	0.10 0.18	0.15 0.40	0.45 0.70	0.50 0.75	0.40 0.60	0.22 0.35	max. 0.040	max. 0.040	max. 0.025
ECH1, 2, 3	0.12	0.33	0.58	0.57	0.47	0.30	0.011	0.008	0.014
ECH4	0.14	0.27	0.58	0.65	0.45	0.29	0.008	0.015	0.018

1.2. Steam piping bend of CSN steels 15 128

As experimental material steam piping bend from fossil fuel power plant, which was operated in conditions of creep damage for 21.1 years, was chosen. The remove of the bend from steam piping was based on the nondestructively measured 1 % creep deformation that has been measured during a planned shutdown. The dimension and operating parameters of the steam piping bend are shown in **Table 2**. From the steam piping bend had been cut off four parts (rings) which were used for experimental sampling. The rings can be described as follows. ECH1 ring was removed from a position on inlet of steam into the bend, ECH2 ring from a position of maximum bending and the measured 1 % creep deformation, ECH3 ring from a position on outlet of the bend and ECH4 ring was removed from straight part outside of the steam piping bend. Afterwards, the rings were cut into individual segments (area under tension - C; area under compression - D; neutral axis - A, B).

Table 2 Dimensions and operating parameters of the steam piping bend

Dimensions		Operating parameters	
Pipe dimensions [mm]	Ø 324 x 48	Operating temperature [°C]	543
Bending radius [mm]	1 200	Operating pressure [MPa]	17.8
Bending length [mm]	2 500	Operating time [h]	184 969

2. RESULTS OF MATERIAL TESTING

The material was assessed in operationally exposed state and in the state after laboratory ageing without tension. The second state was carried out because of monitoring an impact of changes in microstructure on the mechanical properties induced by long-term heat exposition. During the laboratory ageing, the material was exposed to long-term isothermal exposure at 600 °C for 2 000 and 5 000 hours in resistance furnace in air atmosphere. The higher temperature than the operating temperature of the steam pipeline (540 °C) was chosen due to acceleration of structural changes.

2.1. Microstructure

Material subjected to the long-term effect of increased temperatures and pressures (creep conditions) is degraded through a process of microstructural changes. One of the processes was tempering of bainitic microstructure accompanied by increasing proportion of pure ferrite and coarsening of carbide precipitates ($M_{23}C_6$ type) along grain boundaries. Thereby, the grain boundary cohesion was significantly weakening.

Depending on the sampling position (position on inlet of steam into the bend, position of maximum bending and position on outlet of the bend) different degree of degradation of the bainitic-ferritic microstructure was observed. The microstructure at the position on inlet of steam into the bend (ECH1 ring) and at straight part outside of the bend (ECH4 ring) was formed with tempered bainite with a maximum 5 % proportion of ferrite with a grain size G7 to 8, without creep cavities. Minimum degraded bainitic microstructure was at position on outlet of the bend (ECH3 ring) formed by bainite with local occurrence of pure ferrite with grain size G9, without creep cavities. In the **Fig. 1** comparison of microstructure on the outer surface of the area under tension in various position of steam pipe bend is documented. Conversely, the most degraded microstructure was detected at position of maximum bending in the area under tension (ECH2C) and towards neutral axis (ECH2A) formed by strongly tempered bainite with 65 % of ferrite with grain size G6 to 7. Also numerous creep cavities oriented at grain boundary were present, see **Fig. 2**. According to ERA technology standard the degree of degradation of this microstructure at the position of maximum bending in area under tension corresponds to class D and the degree of cavitation damaged according to VGB TW-507e standard corresponds to class 2b. Therefore, the resulting residual lifetime of steam piping bend will be determined by the material properties from position of maximum bending. In addition, quantitative stereology was carried by using scanning electron microscope which provided information on the distribution of chromium carbides at grain boundaries and vanadium carbides within grains. This distribution has influences on the mechanical properties.

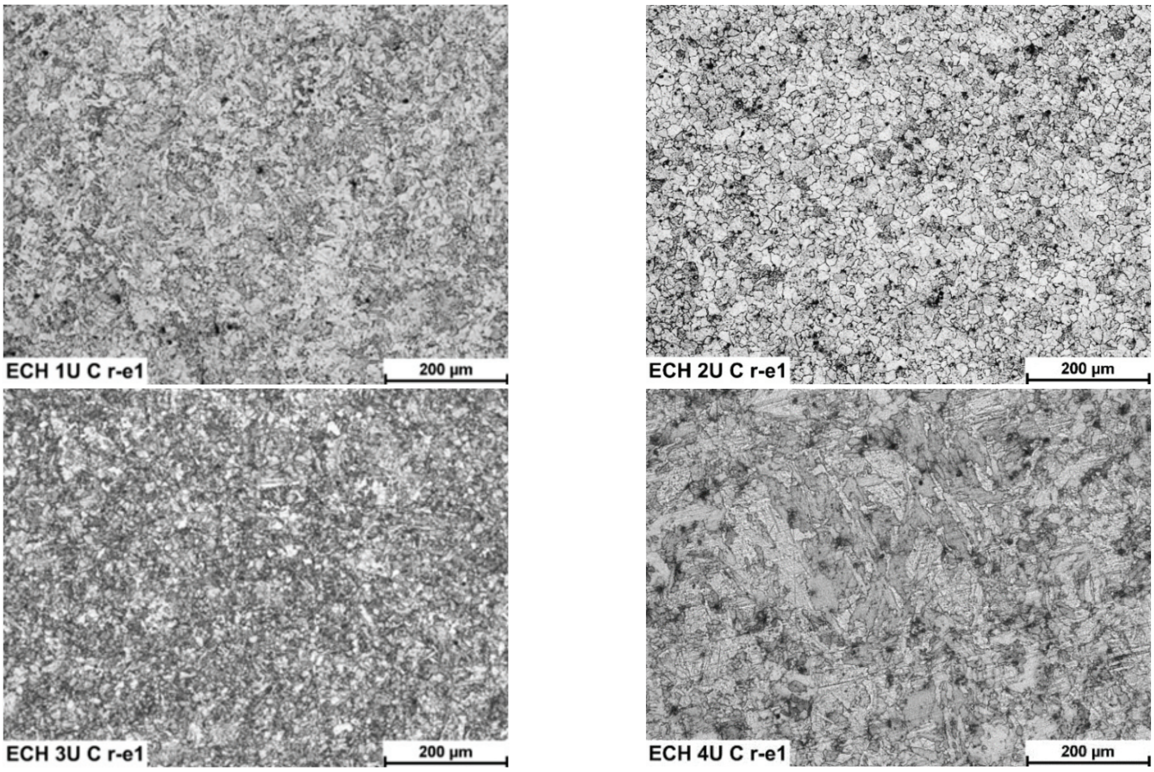
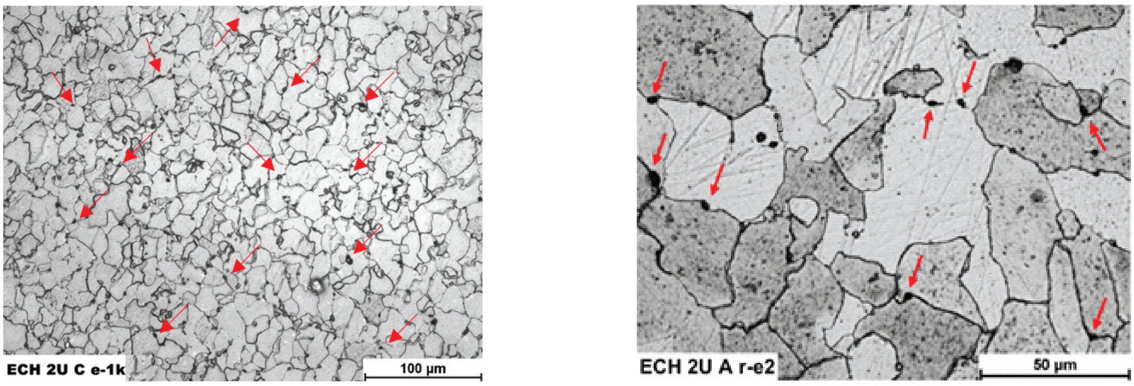


Fig. 1 Comparing of microstructure on the outer surface in area under tension in various position of bend



Collodion replica

Metallographic specimen

Fig. 2 Cavities in place ECH2A and ECH2C on the outer surface

2.2. Mechanical properties

Samples for tensile test were always removed from the near outer and inner surface of the steam pipelines. By monitoring the impact of the sampling site on mechanical properties, we concluded that value of the yield strength and ultimate strength has always been comparable and place of sampling has no impact on the resulting strengths. Complete results of the mechanical properties of steam piping bend are shown in **Table 3**.

Measured values of mechanical properties by tensile test at 20 °C correspond with the identified hardness values and microstructures. The highest strength was measured at position on outlet of the bend (ECH3) with ultimate strength R_m 601 MPa and yield strength R_e 475 MPa. While the lowest strength was measured at position of maximum bending (ECH2) with ultimate strength R_m 462 MPa and yield strength R_e 292 MPa.

In the case of tensile tests at 540 °C (operating temperature steam pipelines) there both yield and ultimate strength decrease was observed, see **Table 3.** At position ECH1, ECH2 and ECH4, the yield strength decreased by approximately 20 % compared with the tensile test at 20 °C. While at position ECH3 yield strength decreased by approximately 45 %.

Table 3 Comparison of real mechanical properties with the standard [1]

Temperature	Mech. properties	ECH1	ECH2	ECH3	ECH4	ČSN 41 5128
20 °C	R_e [MPa]	335	292	475	424	min. 365
	R_m [MPa]	498	462	601	554	490 - 690
540 °C	$R_{p0,2}$ [MPa]	270	202	253	358	min. 206
	R_m [MPa]	405	358	376	423	-
20 °C	Hardness HV	161±3	135±2	194±2	155±2	140 - 197
20 °C	KCV [J/cm²]	70	152	87	25	min. 35

The measured values of mechanical properties were compared with empirical data for steel 15 128 taken from [2] (see **Fig. 3**), with free effective inter-particle distance and with classification of degradation microstructure according to ERA Technology too, see **Fig. 4**. The **Fig. 4** shows that the measured hardness and free effective inter-particle distance corresponds to a defined stadium of degradation microstructure D.

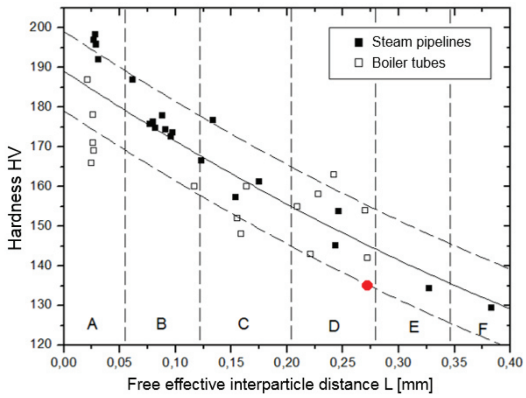


Fig. 3 The dependence of hardness at free effective inter-particle distance at position ECH2C

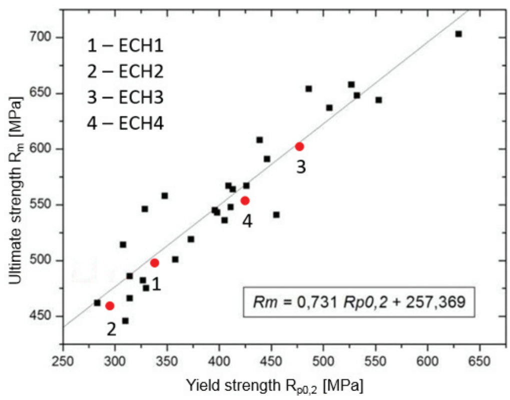


Fig. 4 The dependence of ultimate strength at yield strength (red dots belong to our experimental material)

2.3. Laboratory ageing

Laboratory ageing should help to estimate the influence of microstructure degradation and cavitation damage at microstructure with cavities on the final residual lifetime. Laboratory ageing was done without tension. Therefore the scope of cavitation damage remained unchanged despite an increased in degradation of microstructure. Laboratory ageing for 5 000 hour at 600 °C was reflected only in areas with partially degraded bainitic-ferritic microstructure. There was a further degradation of bainitic microstructure accompanied by a slight increase in the proportion of ferrite with an increase of grain size to one size class G. These structural changes had no significant influence on the mechanical properties. The impact of laboratory ageing on mechanical properties has become visible in the position of the straight part of the steam pipeline (ring ECH4). There was a decrease of ultimate strength by about 11 %.

3. ESTIMATION OF RESIDUAL LIFETIME

Estimation of residual lifetime was done by using Larson-Miller parameter (LMP), Wilshire equations and by using structural standards (ERA Technology, VGB TW-507e).

To estimate a residual lifetime, the maximum stress which was acting on the steam pipeline has to be determined first. In our case, it was tangential stress reached a value of 63 MPa calculated for a thick-walled vessel according to a computational standard.

3.1. According to mathematical approaches

- **Larson-Miller parameter (LMP)**

We used data for steel 15 128 from the document [3] for calculating the material constant C using an iterative method. A value of this constant was calculated 23.8.

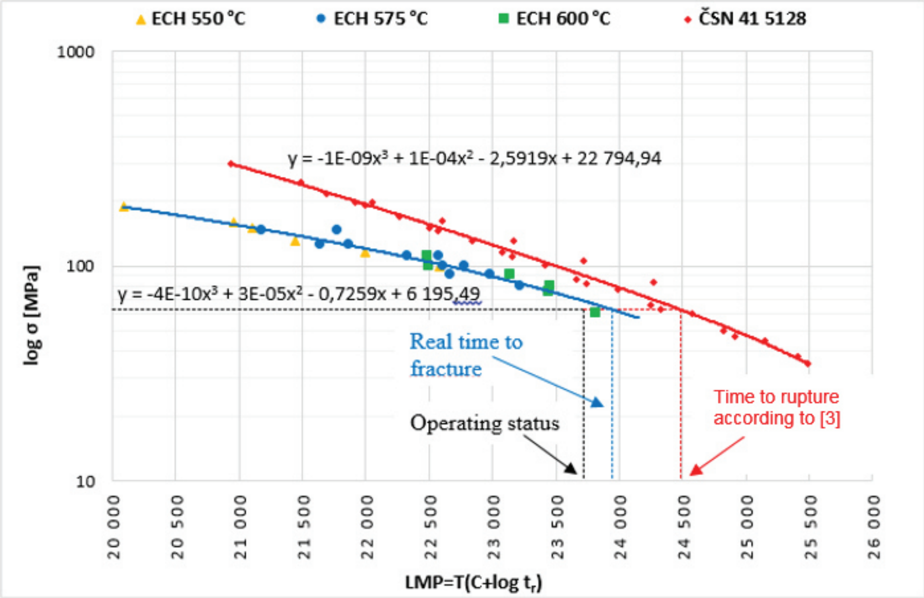


Fig. 5 Estimation of residual lifetime using parameter LMP

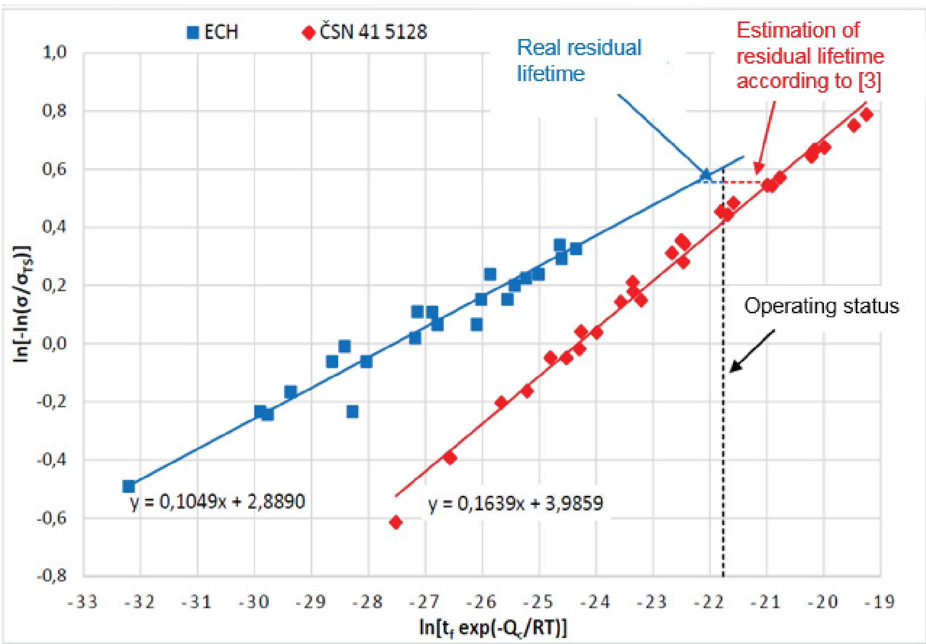


Fig. 6 Estimation of residual lifetime using Wilshire equation

Dependence of stress versus LMP was constructed from data in document [3] (see a red curve in **Fig. 5**) and data from creep-rupture test, from document [4] (see a blue curve in **Fig. 5**). Creep-rupture test was performed on samples collected from the outer and inner surface near of maximum bending the steam piping bend. The **Fig. 5** shows that the values obtained from creep rupture test of samples show lower creep rupture strength than the standard [3] specifies. The material is already degraded and therefore it can be expected that the residual lifetime will be significantly shorter than in the case of estimation from standard data [3]. The value of the residual lifetime of the data mentioned in the document (not operated material) [3] were estimated from the red curve and value of residual lifetime is 1 393 231 hours (159 years). The value is definitely not real, because it is too high. But residual life estimated from the blue curve is 159 972 hours (18.3 years) that is much more likely. So, this results lead us to the conclusion that the steam piping bend was about half of the total life.

- **Wilshire Equations**

The input data was the same as in the case of evaluation according to LMP. An equation (1) was used for a construction of a time dependency of stress, shown in **Fig. 6**.

$$\ln\left[-\ln\left(\frac{\sigma}{\sigma_{TS}}\right)\right] = \ln\left[t_f \exp\left(\frac{-Q_C{}^*}{R \cdot T}\right)\right] \quad (1)$$

Into the equation (1), operation parameters of steam piping bend as operating time t_f 184 969 hours, operating temperature T 543 °C and operating stress σ 62.7 MPa (converted for tangential stress) in a ratio of the measured ultimate strength at temperature 540 °C (σ_{TS} = 358 MPa) were input. From red curve for standard data [3] and from blue curve for experimental data, LM-parameter and residual lifetime were estimated. The residual lifetime is 243 483 hours (27.8 years) for red curve and -71 225 hours (-8.1 years) for blue curve respectively. These results certainly do not correspond to the reality at all.

3.2. According to standards approaches

According to ERA technology standard the degree of degradation of the microstructure at the positon of maximum bending steam piping bend corresponds to class D, which corresponds to large carbides at grain boundary and eliminating morphological differences between original ferrite and bainitic areas. It corresponds to the range of hardness 148 - 166 HV10 as well. The classification (D) means the residual life of 40 % of total lifetime and regular checks after 35 000 hours. According to VGB TW 507e standard the degree of cavitation damaged at the positon of maximum bending steam piping bend corresponds to class 2b (i.e. numerous creep cavities randomly oriented at grain boundary - more than 150 cavities per mm^2). Likely, this class of degradation according to ERA Technology standard (class 2-3) represents to the residual life of 50 % of total lifetime and regular checks after 15 000 hours.

4. CONCLUSION

The resulting residual lifetime of steam piping bend was determined at position of maximum bending, where examined material showed the worst structural and mechanical properties. **Table 4** summarizes all the results of estimated residual lifetime and the recommended frequency of checks. We propose the following recommendations based on state of the steam piping bend with 1 % creep deformation and estimated residual lifetime:

- If the steam piping bend complies with the other NDT controls, it is not necessary replace the bend after measuring 1 % creep deformation and it can be operated longer with respecting interval of the checks.
- Control of degradation microstructure should be carried out in locations nearby to both neutral axes. Although the most frequent occurrence of cavitation damage on the area under tension at the position of maximum bending is totally correct.

Table 4 Summary of the results of estimating of residual lifetime

Approaches	Method	Degradation class	Residual lifetime	Measures
Mathematical	LMP	-	1 393 231 h *	-
		-	159 972 h **	-
	Wilshire	-	243 483 h *	-
		-	-71 225 h **	-
According to	ERA Technology A	D	40 % of total lifetime	Checks after 35 000 hours
	ERA Technology B	2 - 3	50 % of total lifetime	Checks after 15 000 hours
	VGB TW 507e	2b	-	-

* Estimated value of material data of standards ** Estimated value from the data creep-rupture tests

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