THERMAL HISTORY AND STRESS STATE OF A FRESH STEAM-PIPELINE INFLUENCING ITS REMAINING SERVICE LIFE

by

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The service life of thick-walled power plant components exposed to creep, as is the case with pipelines of fresh- and reheated steam, depend on the exhaustion rate of the material. Plant operation at elevated temperatures and at temperatures below designed temperatures all relates to the material exhaustion rate, thus complicating remaining life assessment, whereas the operating temperature variation is a most common cause in the mismatching of real service and design life. Apart from temperature, the tube wall stress is a significant variable for remaining life assessment, whose calculation depends on the selected procedure, due to the complex pipeline configuration. In this paper, a remaining life assessment is performed according to the Larson-Miller parametric relation for a ∅324×36 pipe bend element of a fresh steam-pipeline, made of steel class 1Cr0.3Mo0.25V, after 160.000 hours of operation. The temperature history of the pipeline, altogether with the pipe bend, is determined based on continuous temperature monitoring records. Compared results of remaining life assessment are displayed for monitored temperature records and for designed operating temperature in the same time period. The stress calculation in the pipe bend wall is performed by three methods that are usually applied so to emphasize the differences in the obtained results of remaining life assessment.

Key words: *remaining life assessment, creep, pipeline, thermal power plant*

Introduction

Thick-walled power plant components, as are pipelines of fresh- and reheated steam exposed to creep, are designed for reliable operation at increased temperature and constant pressure. Working conditions of the pipeline are such that static, dynamic, and thermal loads develop from pressure, increased temperature, dead weight, external loading defined by the support-suspension system, and periods of start-up and shutdown [1]. Owing to the complexity of operating conditions, pipelines are exposed to aging processes and damage from creep and fatigue, *i. e.* gradual degradation in the performance ability and reliability. By

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rule, thick-walled components are of high risk, whose failure is to be avoided by regular monitoring their in-service state by non-destructive testing and periodical inspection of the support-suspension system. The basic criterion used as a reference for assessing the performance ability and reliability is the remaining life, an essential criterion for service life management.

The assessment of remaining service life is usually based on data of operating temperature and pipe wall stress, material characteristics, and thus assessment methods are numerous. Depending on temperature records and methods for determining stresses, the results of remaining life assessment may differ significantly. They can be too optimistic or too conservative. In this paper, the obtained remaining life assessment results are compared for a pipe bend element of the fresh steam pipeline, for the supposed and real temperature history, and for different data on pipe bend wall stress, determined by applying the three methods. The goal is to present a critical review on the obtained results and to estimate their credibility.

Background

The true operating life of the steam pipeline usually differs from the designed life and depends on the material exhaustion rate for component operating conditions [2]. Actually, the exhaustion rate of the pipeline predominantly is subjected to the ongoing creep process, while other damage mechanisms account for 20% at the most [3]. Every discrepancy in the designed temperature, or operation at decreased or increased temperature caused by temperature and pressure fluctuations during normal and transition regimes, alters the wear rate of the component. Deviations of the operating temperature, or the temperature operating history of the steam pipeline are the most common cause in the discrepancies between the real and designed service life.

Apart from temperature, the component wall stress is another significant variable in the wear rate, induced by various types of mechanical and thermal loads. Due to the complex spatial configuration of the steam pipeline, the stress state in individual elements may be very difficult to calculate without the knowledge of variables that can be measured (*e. g.* deformations) that are usually not determined because of many reasons. Hence, stress calculation results in the component pipeline wall depend on the selected calculation method and its limitations.

In this paper, a fresh steam pipeline from a 125 MW power plant is investigated, made of low alloyed low-carbon steel of class 1Cr0.3Mo0.25V (12H1MF-GOST) designed for 100.000 hours at 540 °C and pressure of 151 bar. The assessment of remaining service life of the chosen ∅324×36/R = 1600 mm pipe bend element is performed after ~160.000 hours of operation. Up to assessment, the installation had 383 transitions from cold condition and 178 transitions from the hot condition [4]. The well known Larson-Miller parametric relation is chosen for remaining life assessment, whose application incorporates data of the material, operating temperature and pipe wall stress. Having in mind that one of the goals in this paper is to show the temperature influence on the remaining service life, the pipeline including the pipe bend temperature record history is determined based on readings from continuous temperature monitoring.

The pipe bend wall stress is determined by applying three methods that are usually applied for pipeline components: standard calculation according to TRD 300 code that takes in consideration only the internal pressure, calculations according to ANSI/ASME B 31.1 that takes in account also the external loads and thermal stresses, and structural analysis by finite element method (FEA) for pipe bend 3-D modelling. The remaining service life assessment of the pipe bend is made for the case of unknown temperature record history, under the assumption that the pipeline has operated constantly at designed temperature, and also in the case of a known temperature record history. Apart from temperature influence, assessments considered influences from all of the three obtained solutions for the pipe bend wall stress.

Testing methods and calculations used in the remaining service life assessment

Material and testing methods

Components made of low alloyed steel 12H1MF have good resistance to creep and are not susceptible to oxide formation, so this steel has found wide use in the manufacture of parts of thermal power plant components that operate up to 560 °C and at pressures up to 20 MPa [2, 5]. This steel starts to exhibit creep effects if a constant stress is applied along with a temperature above 500 °C, where the creep deformation will develop in the direction of the acting stress. Changes in the material in this process are: diffusion creep (inside boundaries), grain boundary slip, and dislocation creep (dislocation movement). A final result of these processes is increased deformation of the grain, considerable changes in the composition, and a distribution of secondary carbide phase, as well as the occurrence of pores at grain boundaries. Apparently, the coalescence of pores leads to the formation of microcracks that finally cause the fracture of the component.

Zones primarily monitored for creep are welded joints and pipe bends, and other components exposed to stress concentrators and stresses that have resulted from assembly.

As basis for remaining service life assessment, non-destructive testing results are frequently used and should show the state of the component metal, from the aspects of existing macroscopic damage, microstructural degradation and micro damages. The selected pipe bend element is tested by ultrasonic and magnetic methods for detecting volumetric and surface flaws of considerable size that may indicate a large degree of damage and require the application of other measures for evaluating its performance ability [6]. Also, a full dimensional inspection of the pipe bend element is also carried out, microstructural states are determined by the replication method and hardness tests are performed in a precisely defined range and at test locations. These test results are used for determining the pipe bend wall stress for all three applied methods, and for evaluating the degree of material deterioration.

Methodology approach for determining operating temperature and pressure

For thermal power plant components designed for creep strength it is very important to define the precise operating times at certain temperatures and pressures, since these are the basic data for calculating the wear by methods based on service life fractions or by parametric relations [4, 7]. During operation, particularly during transition regimes and below nominal boiler productivity, the operation temperature changes such so that each component is, despite that most of the time it operates at nominal temperature, at certain time intervals exposed to temperatures that are higher or lower than nominal. Hence, the continuous recording system for operating temperatures and pressures is a mandatory part of installation monitoring. Data acquisition gains significance only when records are treated systematically. The most appropriate data treatment is by determining the operating time at defined temperature and pressure intervals. Accordingly, in this paper it is adopted that the systematization of the acquired operating parameters is performed for temperature intervals of 10 °C increments and pressure intervals of 5 bar increments. Usually, operation parameter readings are performed in a time interval significantly shorter than total exploitation time, and an assumption is introduced that the installation has operated under the same regime during its whole operational life [4, 7].

Methods for stress state calculation

Determination of the stress state enables a more precise analysis of component behaviour in operation, since the nature of its wear directly depends on the acting stress.

The calculation of stress in a tension zone of the pipe bend of specified size under acting internal pressure, according to TRD 300 standard, is made by applying the well known expression:

$$\bar{\sigma}_{\mathrm{a}} = \frac{p(d_{\mathrm{a}} - s_{\mathrm{vi}} - s_{\mathrm{va}})}{2s_{\mathrm{va}}\nu_{\mathrm{N}}} \frac{2R + 0.5d_{\mathrm{a}} + 0.5s_{\mathrm{vi}} - 1.5s_{\mathrm{va}}}{2R + d_{\mathrm{a}} - s_{\mathrm{va}}} + \frac{p}{2} \leq \sigma_{\mathrm{all}} \tag{1}$$

where p is the internal pressure, d_{a} – the outer diameter, s_{vi} – the thickness of bend pressure zone, s_{va} – the thickness of bend tension zone, ν_{N} – the coefficient of weakening, R – the pipe bend curvature radius, and σ_{all} – the allowed stress.

Structural analysis of the steam pipeline is often done by applying dedicated computer software, with relatively simple mathematical modelling of the pipeline and by numerically solving a system of equations. Due to the complexity of the spatial linear system model of the pipeline, the stress state analysis requires a previous calculation of internal forces and moments, best performed by finite element method. Stress analysis is done according to one of the standards in this field, while ASME/ANSI B 31.1 is used in most cases. Pipeline isometric drawings with a layout of support locations, types and characteristics, measurements of support/suspension locations during operation (hot condition) and during stoppage (cold condition), as well as measured wall thicknesses and diameters [4, 8], all serve as the basis for stress state analysis of the tested pipe bend element. According to this standard the allowable stress range, σ_{A}, is given by:

$$\sigma_{\mathrm{A}} = f(1.25\sigma_{\mathrm{C}} + 0.25\sigma_{\mathrm{h}}) \tag{2}$$

where: σ_{C} is the basic allowed stress of the material at the lowest temperature in the operation cycle (cold condition), σ_{h} – the basic allowed stress of the material at operation temperature (hot condition), and f – the stress reduction factor in the case of cyclic loads on the pipeline from thermal dilatations for a total number of cold start-ups N during its service life.

For determining the stress state of the pipeline, according to the standard, the stress from static loads is defined such that it includes effects of internal pressure, dead weight and other static mechanical loads, and must satisfy:

$$\sigma_{\mathrm{SL}} = \frac{pd_{\mathrm{a}}}{4s_{\mathrm{va}}} + \frac{0.75iM_{\mathrm{A}}}{Z} < 1.0\sigma_{\mathrm{h}} \tag{3}$$

where σ_{SL} is the stress from static loads, d_{a} – the measured outer pipe diameter, s_{va} – the measured wall thickness of the component, M_{A} – the resulting moment from weight and other static loads, i – the stress intensification factor, and Z – the section modulus.

The stress from thermal dilatation must satisfy eq. (4):

$$\sigma_{\mathrm{E}} = \frac{iM_{\mathrm{C}}}{Z} < \sigma_{\mathrm{A}} + f(\sigma_{\mathrm{h}} - \sigma_{\mathrm{SL}}) \tag{4}$$

where σ_{E} is the stress from thermal dilatation, M_{C} – the range of resulting moment from thermal dilatation with support displacement, and f – the reduced stress range factor.

The total stress, σ_{T}, that results from the cumulative effect of thermal stress, weight, internal pressure, and other static mechanical influences, must satisfy:

$$\sigma_{\mathrm{T}} = \sigma_{\mathrm{SL}} + \sigma_{\mathrm{E}} < \sigma_{\mathrm{A}} + \sigma_{\mathrm{h}} \tag{5}$$

Stress state analysis of pipeline elements can be made by modelling the walls by finite elements of the shell type or by 3-D finite elements. Modelling with shell type finite elements is much easier and is applied in situations when pipeline walls may be considered as thin shells. The tested pipe bend in this paper is treated by 3-D model finite elements for a more precise determination of the stress state that originates from internal pressure, including stress changes through wall thickness. Stresses in the mesh elements are determined as equivalent Von Mises stress.

Larson-Miller parametric relation for remaining life assessment

Material behaviour is defined in conditions of creep, or for the creep stage process determined by the amplitude and rate of creep deformation. In practice it is custom that material behaviour in the state of creep is determined based on accelerated tests at temperatures and pressures that are much higher than operational, thus deriving the creep rate-time dependence for a given combination of temperature and stress. Data received from accelerated tests are subsequently extrapolated by applied parametric methods to real operating conditions. A whole sequence of parametric methods has been developed that enable extrapolation of results from accelerated creep tests at elevated temperatures (Larson-Miller, Manson-Haferd, Manson-Succop, Orr-Sherby-Dorn, *etc*. [4, 9-12]). The compared results received from these time-temperature parameters have concluded that they are almost completely identical. The most familiar and often used parameter is the Larson-Miller parameter (*LMP*), derived from the relation for minimal creep deformation rate:

$$\dot{\varepsilon} = \mathrm{A}_1 \exp\left(-\frac{Q}{\mathrm{R}T}\right) \tag{6}$$

where $\dot{\varepsilon}$ is the creep rate, A_1 – the experimental constant depicting material strengthening, Q – the creep activation energy, R – the universal gas constant, and T – the temperature.

In order to derive the relation between minimal creep rate and time to fracture, the Monkman-Grant relation is used that is valid in the case when rupture occurs after a long period of exploitation in conditions of low stresses:

$$t_{\mathrm{f}}\,\dot{\varepsilon}_{\min} = \varepsilon_{\mathrm{s}} = \mathrm{const} \tag{7}$$

where t_f is the time to fracture, and ε_s – the Monkman-Grant constant. Equation (7) allows to determine the remaining service life based on knowledge of material deformation characteristics.

By replacing eq. (7) in eq. (6) and substituting $\mathrm{A}_2 = \mathrm{A}_1/\varepsilon$ we get the time to fracture, t_f:

$$t_\mathrm{f} = \mathrm{A}_2^{-1}\exp\left(\frac{Q}{\mathrm{R}T}\right) \tag{8}$$

and by applying the logarithm to both sides:

$$\log t_\mathrm{f} = -\log\mathrm{A}_2 + \frac{Q}{\mathrm{R}}\frac{1}{T} \tag{9}$$

Equation (9) represents a linear dependence between log t_f and $1/T$ at constant stress, and the ratio Q/R represents the slope of this line. By applying further simple substitutes we get the Larson-Miller parameter than can be expressed as:

$$LMP(\sigma) = T(\log t_\mathrm{f} + \mathrm{C}) \tag{10}$$

where $LMP(\sigma)$ is the Larson-Miller parameter and C – the material constant than takes the values of 15-25 [13].

Time to fracture at constant stress changes with temperature so that the Larson-Miller parameter remains a constant for the given stress. For describing the *LMP* and stress dependence it is convenient to use the polynomial function of the type:

$$LMP(\sigma) = \mathrm{C}_1 + \mathrm{C}_2\log\sigma + \mathrm{C}_3\log\sigma^2 + \ldots + \mathrm{C}_\mathrm{n}\log\sigma^{n-1} \tag{11}$$

where C_1-C_n are constants for a given material type. These constants are determined by the method of least squares from data on the applied stress at accelerated creep tests and time to fracture. For low alloyed heat resistant steels, eq. (11) is usually reduced to a second order dependence [14].

When steels are concerned, generally it is adopted based on experimental results that the constant C in eq. (10) takes the value around 20 [13]. However, referring to published data, the C value for the *LMP* expression in the case of 12H1MF steel is 20.62 [15].

In order to fully apply the service life calculation procedure (time to fracture) by using the Larson-Miller parameter, it is necessary to know as precisely as possible the steam pipeline operating stress and temperature. Also, because of temperature fluctuations, it is necessary to apply a correction and determine the equivalent time value for the nominal temperature for every time spent at a specified temperature. In this way, the input variable for the remaining service life calculation is a single operating temperature value and a corresponding equivalent exploitation time. The service life calculation by *LMP* method is performed in following steps:

- the analysed component operating parameters are defined (temperature and stress), and the exploitation time for these parameters,
- the *LMP* value is evaluated for the calculated stress, and
- based on the *LMP* value, by applying eq. (10), the time to fracture t_f is calculated (remaining life).

Results

Component operation parameters

In the course of determining operating conditions of the fresh steam pipeline, along with the pipe bend element, for which the remaining service life assessment is performed, the measured operating temperatures and pressures are analysed for a 5 consecutive year period (~26.000 hours). The time that the steam pipeline has operated at a certain temperature is read from tapes that continuously record temperatures and is systematised into temperature intervals of Δ*T* = 10 °C for the sake of extrapolating on the total service life of 160.000 hours, tab. 1 [7]. The distribution of service time fractions of the fresh steam pipeline at certain temperature intervals is shown in fig. 1. Since the operating fluid pressure, in the records, did not show any significant variations, except during transition regimes, a mean operating pressure value of 135 bar is adopted for calculation.

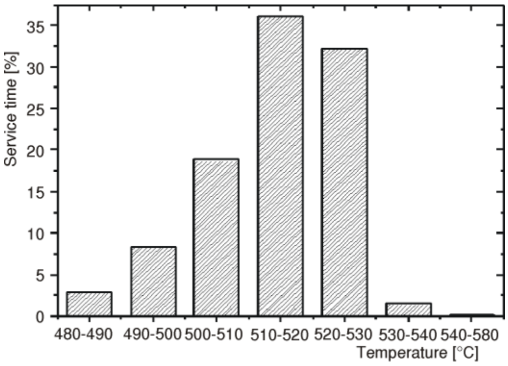


Figure 1. Distribution of operating time fractions of the fresh steam pipeline at certain temperature intervals

Table 1. Operating time in temperature intervals extrapolated for the total service life

Δ*T* [°C]	480-490	490-500	500-510	510-520	520-530
Time [h]	4646	13384	30134	57790	51548
Δ*T* [°C]	530-540	540-550	550-560	560-570	570-580
Time [h]	2315	50	25	9	174

The determination of the equivalent time for recorded time values of all temperature intervals of the temperature history on the nominal steam pipeline temperature of 540 °C is performed by applying the *LMP* relation, eq. (10). Each processed time spent at temperatures lower than nominal is actually shorter than the real (the component wears out slower), hence, each time spent at temperatures higher than nominal is longer than real (the component wears out faster). The summation of the times received by processing for each temperature interval gives data on the total equivalent time the component would spend if it had operated all of the time at nominal temperature. Taking into account the data from tab. 1, we receive the equivalent time the pipe bend element would spend if it had operated at 540 °C, equal to ~95.000 hours.

Non-destructive testing

Ultrasonic and magnetic particle testing has not discovered neither volumetric nor surface flaws in the selected pipe bend, and from this point of view it is clear that the pipe bend has a fair integrity. Dimension inspection results of wall thickness, *s*, and diameter, d_a, tab. 2, have shown that the minimal measured thickness value is located in the bend tension zone, equaling 33.5 mm, which is the basis for relevant stress calculation and remaining service life assessment. The outer diameter value, measured at the same cross-section, is 324.6 mm, which also is the input value for determining the stress in the pipe bend wall. Measured hardness values, tab. 2, show that the lowest value is close to the lower allowed $HB_{\text{min.}} = 130$. This fact indicates that during long term operation of 160.000 hours at elevated temperature, microstructural degradation has occurred to a certain level, which has been confirmed by the surface microstructure replication method, tab. 2.

The material's microstructure is ferritic of uneven grain size with partially spheroidised pearlite and carbides. Some slip lines are noticed in particular ferrite grains, whose presence indicates an ongoing plastic deformation process [4].

Table 2. Pipe bend non-destructive test results

	Test method				
	US/MP	s, [mm]	d_a, [mm]	Hardness HB	Microstructure
Result	No traces	33.5-36.1	324.1-324.7	127-146	Ferrite + pearlite + carbides + slip lines

Table 3. Pipe bend characteristics – RA line

Nominal size $\varnothing d_{an} \times s_n$, [mm]	$\varnothing 324 \times 36$
Measured size $\varnothing d_a \times s_{min}$, [mm]	$\varnothing 324.6 \times 33.5$
Curvature radius R, [mm]	1600
Material	1Cr0.3Mo0.25V
Designed pressure p_d, [MPa]	15.10
Operating pressure p, [MPa]	13.5
Designed temperature T_d, [°C]	540
Young's modulus E (540 °C), [MPa]	$1.775 \cdot 10^5$
Young's modulus E (20 °C), [MPa]	$2.1 \cdot 10^5$

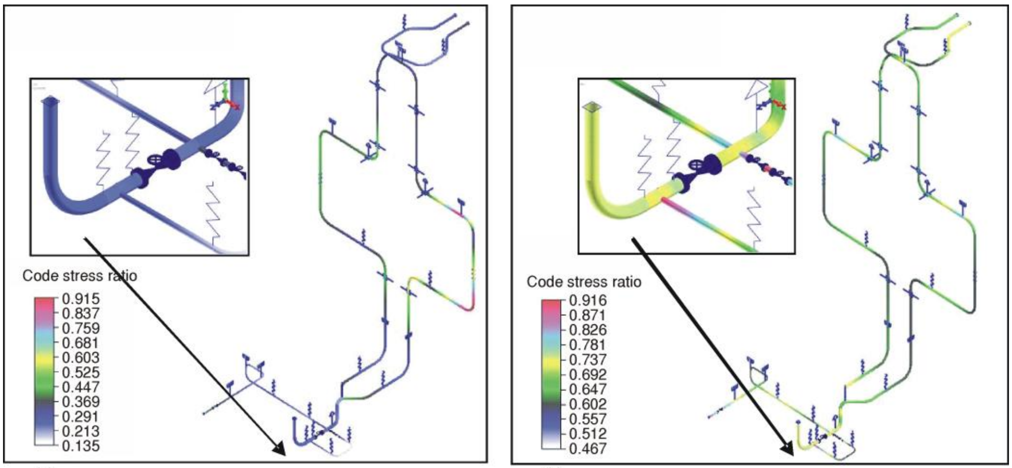
Stress analysis of pipe bend

Input data for evaluating the relevant stress in the pipe bend wall for remaining service life assessment, according to all three mentioned methods, are given in tab. 3.

The relevant operating stress according to TRD 300 standard is calculated, eq. (1), for operating parameters and measured sizes of the pipe bend element, and it equals 55.6 MPa.

The stress state calculation according to ASME/ANSI B 31.1 is made based on measurements of support locations in the hot and cold condition for the fresh steam pipeline along with the pipe bend element, for which the remaining service life assessment is carried out by applying ALGOR software. Results are illustrated in fig. 2.

The pipe bend element in hot condition, describing the operating state, fig. 2(a) (the bend is depicted by an arrow), is at a location distinguished by a relatively low stress state. However, the stress state of the same pipe bend element in cold condition, fig. 2(b), that describes the stoppage and start-up/shutdown regimes of the installation, is unfavourable, pointing out that the pipe bend is exposed to some additional loading. The extracted pipeline layout with marked support locations and joint in front of the pipe bend is the most probable cause of the depicted elevated stress state. Load calculation is performed for the three cases, taking into account: (1) dead weight of pipeline with insulation, internal pressure, thermal dilatations, and displacements at joint locations, (2) dead weight of pipeline with insulation and internal pressure, and (3) thermal dilatation and displacements at joint locations. The calculated-allowed stress ratio is determined in all of the three cases, tab. 4, and shows the calculated stresses to be within allowed limits according to standard for all three methods of load calculation. Calculated stress values are used to evaluate the relevant stress in the pipe bend wall, 62.3 MPa, which is the stress value adopted for the remaining life assessment.



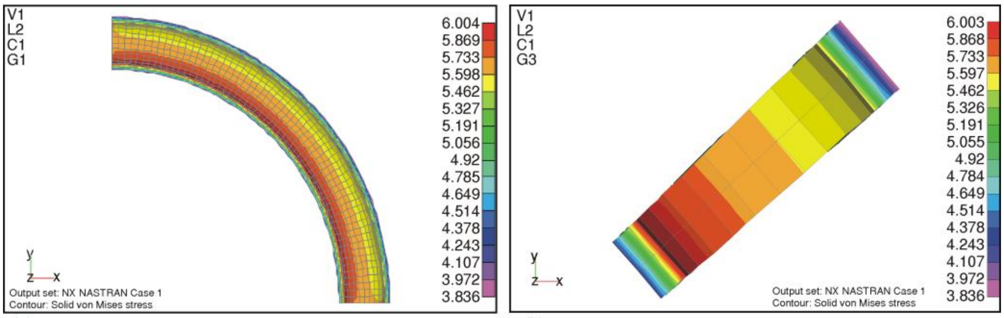
(a) (b)

Figure 2. Linear stress analysis of the fresh steam pipeline along with the pipe bend element; (a) stress state at hot condition; (b) stress state at cold condition

Table 4. Input stress values for evaluating relevant stress

Case	Allowed stress according to ASME section 31.1	Allowed stress [MPa]	Calculated stress [MPa]	Ratio calculated/allowed
1	$\sigma_h + \sigma_A$	216.6	198.3	0.92
2	σ_h	60.8	55.7	0.92
3	$\sigma_E \leq \sigma_A + \sigma_h - \sigma_{SL}$	180.8	162.5	0.90
Relevant stress in the pipe bend wall σ_M, [MPa]			62.3	

A 3-D structural analysis of the fresh steam pipe bend element stress state is performed by finite element method (FEA) with NASTRAN software. The calculation is performed for operating parameters and measured sizes. The stress distribution in the pipe bend and in the highest loaded section, corresponding to the angular point in the tension zone of the pipe bend element, is shown in fig. 3. The maximal calculated Von Mises stress value of the highest loaded section equals 48.49 MPa, and is adopted as the stress value for remaining service life assessment of the pipe bend.



(a) (b)

Figure 3. Stress distribution, (a) in the pipe bend element; (b) in the highest loaded cross-section of the pipe bend element (color image see on our web site)

The resulting values of relevant stresses in the highest loaded zone of the pipe bend for all three methods (TRD 300, ANSI/ASME B31.1, and FEA) are given in tab. 5.

Based on results shown in tab. 5 it is obvious that the stress values differ considerably, which will certainly reflect on the results of the evaluated remaining service life. These differences come as a result of the applied methods having essential differences in their initial grounds.

Table 5. Relevant stresses for evaluating the remaining service life

Stress calculation according to:	TRD 300	ANSI/ASME B.31.1	FEA
Designation	σ_{hs} [MPa]	σ_M [MPa]	$\sigma_{VM,\ max}$ [MPa]
Relevant stress value	55.6	62.3	48.49

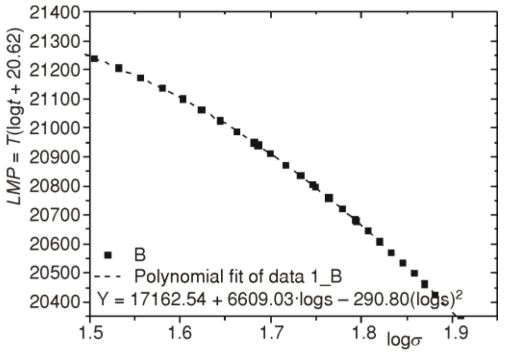


Figure 4. *LMP*–σ function at 540 °C for 12H1MF steel

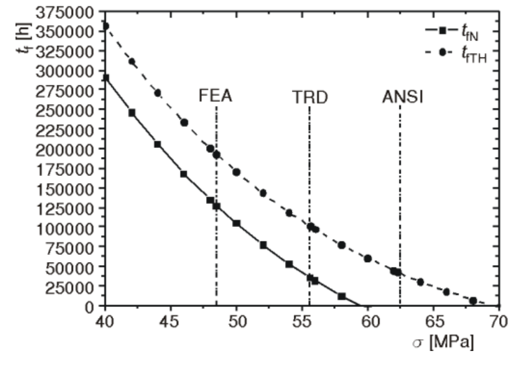


Figure 5. Time to fracture for three relevant stresses and real spent time (t_{fN}), *i. e.* the equivalent operating time for the temperature history (t_{fTH})

Remaining service life assessment

The remaining service life of the fresh steam pipe bend element is assessed by applying the Larson-Miller parametric relation, eq. (10), for two case variants. In the first case, the temperature of 540 °C is adopted as constant value for total 160.000 hours of operation, which is common practice when the temperature history is not known, and by varying the relevant stress, tab. 5. In the second case, the temperature history is taken into account and the equivalent operating time of 95.000 hours at 540 °C, with variation of relevant stress, tab. 5.

The *LMP*–logσ dependence for 12H1MF steel at 540 °C, according to eq. (11) with n = = 3, is plotted based on data from literature – for accelerated creep tests for this steel [2, 5], fig. 4.

For all of the three values of relevant stresses in tab. 5, values of *LMP* parameters are taken from the plot in fig. 4 and used for determining the remaining service life and the spent time of 160.000 hours and equivalent time based on temperature history, fig. 5. Values of stress determined by all three methods are marked in fig. 5, and results of the calculated remaining service life are given in tab. 6.

As based on results of remaining life, tab. 6, for the selected fresh steam pipe bend element, evaluated from the *LMP* relation and from three different methods for determining stresses in the component wall (TRD 300, ASME/ANSI B 31.1 and FEA) one can state that there is a significant difference among all of obtained results. In the case of real temperature history, the assessed time to fracture is longer for all three relevant stresses. The most unfavourable operating conditions of the component, and hence, the shortest remaining service life is achieved by calculating the stress state according to ANSI/ASME B 31.1, while FEA calculations give the most optimistic results.

Table 6. Evaluated remaining service life

Operating time	Time to fracture, [h]		
	TRD	ANSI/ASME B31.1	FEA
t_{fN} – 160.000 h	30955	Material wear	120760
t_{fTH} – 95.000 h	96046	38914	185851

Discussion

Methods for remaining service life assessment should generally include, not only the evaluated material creep characteristics, but also should analytically describe the creep process in much sense as possible. This complex task can be solved only by application of phenomenological equations, in which the cumulative effect of the basic physical laws influencing the development of plastic deformation and material degradation during creep are statistically reviewed at the highest possible level. The sequence of simplified relations that describe the creep process for a given class of steels at certain temperature and stress ranges is developed from basic equations that describe deformation and damage processes, and finally enable to determine time to fracture. These relations are mostly simple enough for practical use and for describing the temperature-time dependence of temporal characteristics for a sufficiently wide temperature and time interval. Nevertheless, one of the widely used is the Larson-Miller relation, applied in this paper, just so because of simplicity sake and the fact that it is based on material characteristics that are usually determined [4, 10, 16].

Since, as stated, the *LMP* relation used for determining time to fracture, the temperature function, time, and stress, it is clear that the accuracy of temperature and stress input data shall be decisive for reliable time to fracture assessment. It has been found that the temperature is the basic exploitation parameter for operative diagnostics, influencing material performance ability. When real temperatures are higher than the designed, component service life is significantly shortened due to processes of accelerated degradation of nominal material characteristics. In practice, during operation, it is necessary to monitor deviations of the designed temperature that may reach maximal values in periods of non-stationary operating regimes, *e. g.* at start-up, shutdown, and varied steam generation. Still, temperature oscillations occur in periods of relatively stable operation, *e. g.* metal temperature variations of 20 °C and occur more during loading variations of the boiler. It should be noticed that a 5 °C temperature increase relative to the pre-calculated value causes a 25-30% shortening of the time to fracture for austenitic steels, and 35-40% for ferritic-pearlitic steels [2]. Similarly, a 15 °C increase (from 540 to 555 °C) leads to a 25-30% drop in creep strength depending on the steel type.

Steel properties at elevated temperatures generally depend on the temperature history that begins in the fabrication phase with heat treatment and continues during operation at temperatures that only in the long term, as heat treatment, lead to microstructural changes [17]. During heat treatment that usually includes quenching or normalization, followed by tempering, the structure of low-alloyed low carbon heat resistant steel is in the state of a quasi-static equilibrium, and further exposure to elevated temperatures during operation enhances the process that has originated in heat treatment, theoretically until reaching a totally balanced structure that is, in the case of pearlitic steels, a totally deprived ferritic matrix with a uniformly distributed carbide phase. This analysis that includes only the temperature history is not suitable for perceiving the real state of real components after long term operation. The influence of stress is of great significance since temperature activated processes accompanied by stress become directional and tend to accelerate, leading to specific types of microstructural changes and damages that totally wear-off the metal, before reaching the theoretical state of equilibrium.

The equivalent time, evaluated by taking into account the temperature history of the pipeline, by no doubt indicates that the real spent service life is considerably shorter than the 160.000 hours, the installation has already operated. This fact indicates not only the importance of monitoring, but also the determination of equivalent exploitation time at nominal temperature, representing a necessary fact in the remaining service life assessment and the moment for apparent component replacement [2].

Owing to the constant ongoing dynamic process in the material during component operation, approaches that do not consider the fact that material characteristics change during time, cannot give adequate results of the remaining service life assessment procedure. Alternatively, microstructural evaluation alone by classical methods, as surface replication and sampling, is not sufficient for predicting time to fracture, since research has shown that the microstructure does not change consistently across all zones in the component exposed to elevated temperatures.

Life assessment methods, generally based on stress analysis, do not take in consideration the real structural state of the material, while the applied Larson-Miller parametric relation for remaining service life assessment is a proper microstructural indicator, along with the temperature and the stress state [2, 5].

The described example of evaluating operating stresses according to three methods has indicated that in this case the component wall stress under ANSI/ASME B31.1 based calculations has taken in account the stresses the pipeline has been exposed to in the cold condition, which is not considered in the other two methods [18]. Regarding that microstructural findings have shown pronounced elements of deformation, as reflected in the slip bands of ferritic grains, as well as the fact that the operating stress is not sufficient to cause plastic deformation of this type, it implicates that the acting stress in the cold condition is most probably responsible for these changes. During component operation, stress relaxation takes effect but also the sliding of accumulated dislocations in specific planes that accelerates the deterioration of creep resistance properties. Taking this in account, the stress value calculated by ANSI/ASME B31.1 can be considered rather acceptable than the stress determined by other two methods. Nevertheless, owing to the conservative approach, more realistic calculation results may be achieved if instantaneous material strength properties were to be determined by destructive testing methods, in which case the relevant stress value evaluated by this method would be somewhat lower, and therefore longer evaluated life. Stress calculated by FEA method has the lowest value, since these models based on linear elastic theory do not consider plastic deformation that appears during creep, as well as other conditions taken into consideration by *e. g.* ANSI/ASME B31.1, resulting in the most optimistic remaining service life assessment [19].

In general, the results in this paper indicate that a more certain remaining service life assessment in the particular case is achieved by applying the ANSI/ASME B31.1 standard for stress evaluation, along with microstructural evaluation, and by taking in account temperature history. As the pipe wall stress calculation would take in consideration values of instantaneous material characteristics, the values for the remaining service life would be higher according to this method.

Conclusions

The remaining service life assessment of a fresh steam pipe bend element from a thermal power plant installation, made of steel class 1Cr0.3Mo0.25V is shown. The remaining service life is evaluated by the Larson-Miller parametric method, by varying data of operating conditions of the pipe bend element. Based on results shown here, one may conclude:

- since *LMP* is a time-temperature parameter, the remaining service life value greatly depends on the operating temperature data of the pipe bend element, because operation above or below the designed temperature alters the wear rate of the material,
- knowledge of temperature history, with correlation to microstructural state of the component that depends on it, considerably minimizes the conservatism in this method,
- the selection of an adequate method for determining the operating stress of the component wall, as the second most significant parameter for predicting the remaining life by *LMP* is not always easy to accomplish, owing to specific operating conditions of each particular component, and a wrong choice would lead to over- or under-estimated assessment results, and
- in the case of the pipe bend element shown here, the non-operating state has significantly influenced structural changes in the pipe bend material, and it was most appropriate to determine the stress by a method that considers stresses both in the hot and cold condition.

Generally, it is necessary to devote special effort for the operating parameter data acquisition systems of components exposed to creep, above all, in the aspects of data systematization and their further use. This statement particularly relates to temperature records, where it is obvious from examples in this paper that temperature history greatly "corrects" data of real spent life of the component, most often in the direction of further extending its service life.

Nomenclature

A_1 – experimental constant
C – constant in *LMP* relation
C_1-C_n – constants
f – stress reduction factor
d_a – outer diameter, [mm]
d_an – nominal outer diameter, [mm]
E – Young's modulus, [MPa]
i – stress intensification factor
LMP – Larson-Miller parameter
M_A – resultant moment from static load, [Nmm]
M_C – resultant moment from thermal stresses, [MPa]
N – number of full cycles
p – internal pressure [MPa];
p_d, – designed internal pressure, [MPa]
Q – creep activation energy [kJmol^{-1}]
R – curvature radius, [mm]
R – universal gas constant
$s_\mathrm{min.}$ – minimum measured wall thickness, [mm]
s_va – wall thickness in tension zone, [mm]
$\mathrm{s}_{\mathrm{v}i}$ – wall thickness in pressure zone, [mm]
s_vn – nominal wall thickness in extrados zone, [mm]
T – temperature, [°C, K]
T_d – design temperature, [°C]
t_f – time to fracture, [h]
Z – section modulus, [mm^3]

Greek symbols

ε – creep deformation, [%]
$\dot{\varepsilon}$ – creep rate [%·h^{-1}]
ε_s – Monkman-Grant constant, [%]
ν_N – coefficient of weakening
σ_A – allowed stress range, [MPa]
σ_all – allowed stress, [MPa]
σ_C – basic allowed stress on cold, [MPa]
σ_E – thermal stresses, [MPa]
σ_h – basic allowable stress on hot, [MPa]
σ_M – relevant stress in the pipe bend wall, [MPa]
σ_SL – static load stress, [MPa]
σ_T – resultant stress, [MPa]

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