STRUCTURAL DEGRADATION OF STEAM PIPE BEND MADE OF 0.5Cr-0.5Mo-0.3V STEEL AFTER LONG-TERM CREEP EXPOSURE

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Abstract

A creep damaged area was found during the routine control of the steam pipeline bend of 200 MW fossil-fuelled power plant boiler close to the outer fibre and near the top of the bend. The damaged area with identified creep cracks was about 250 x 600 mm in size and the maximum depth of the cracks was 7 mm. Metallographic analysis carried out in this area confirmed the non-homogeneous cavitation damage. Density of cavities continuously decreased throughout the affected area from the outer to the inner surface of the pipe, around the pipe circumference and also in the axial direction along the length of the bend.

The actual extent of degradation of material properties was then evaluated by testing the mechanical properties, notch and fracture toughness and the results were used to calculate the residual life of the bend. The results of these analyses showed that although the creep damage extent was probably one of the worst, which had been ever detected in the boiler of this type, cracks would propagate through the bend by stable growth until the mid-wall thickness and only then would the final rapid failure occur. This result confirms the possibility of extending the life of the steam pipeline bends far beyond the limits of the currently used criteria.

Keywords: 0.5Cr-0.5Mo-0.3V steel, long-term creep exposure, cavitation, creep damage, residual life.

1. INTRODUCTION

Many of the electricity producing fossil-fueled 110 MW and 200 MW boilers in the Czech Republic are at present time close to or even after their design life. The same is true in case of steam pipelines (some of them have been operating for more than 270 000 hours) and thus the question of prolonged lifetime is of great urgency. While the welded joints of the pipeline have been tested routinely, the attention is now turned to the pipe bends. Effort to reduce the operational costs tends to prolong the overall life of the steam piping or to operate the block at the elevated operating parameters without increasing the safety risks. The result is then the planned terms of repairs and replacements based on the detailed knowledge of the actual material properties with bearing in mind the financial savings resulting from the prolonged lifetime of the steam pipes or increasing their operating parameters as well as the evaluation of the potential risk of premature failure.

Till now, the evaluation of condition of the steam pipeline and planning subsequent inspections and repairs of bends and other critical points have been made according to the standard of CEZ using the evaluation of the degree of creep damage stated in VGB TW 507 [1]. Steam pipeline are to be replaced when the degree of creep damage equals to 3A, which corresponds to the oriented cavities detected by replicas. But such a extent of material degradation can be still far from the real end of life of the pipeline. Therefore, much effort was concentrated in shifting the limiting state of the pipeline from the oriented cavities towards appearance of microcracks. This attempt is also supported by the development of more efficient methods of monitoring of critical parts, including the using of modern NDT methods (TOFD UT, UT LPA, acoustic emission) and also the extension of evaluation methods of material properties (SPT samples, potential method, evaluation of replicas according to NT TR 170 [2], NT TR 302 [3]).

2. TESTED MATERIAL AND ITS PROPERTIES

Damaged areas with cracks on the outer surface of two pipe bends were found during the planned inspection of the steam pipeline of a 200 MW boiler in a coal-fired power plant (see circles in Figure 1). The steam pipeline was made of pipes Ø 324 x 48 mm of steel grade 15 128.9 and was operated at 540 °C with a steam pressure of 17.3 MPa for more than 240,000 hours. In the case of bend No. 17 there was a large area affected by a mesh of cracks, while in the case of bend No. 21 the defective area was only local. In both cases the damaged areas were adjacent to the outer fibre of the bend, but did not directly lie on it.

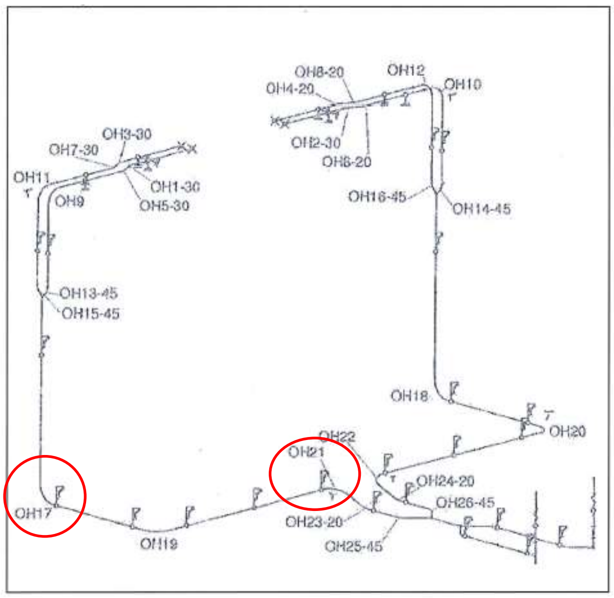

Fig. 1 Scheme of left and right branch of the steam pipeline with damaged bends

The complex of material properties including creep strength was tested in order to obtain as much material data as possible and to use the results as the reference for the intended prolongation of the safe life of the pipelines and to set new life limiting criteria of the steam pipeline bends made of this steel grade, which is still the most frequently used material in Czech coal-fired power stations. The results of the bend No. 17 with the massive creep damage are presented here.

2.1. Chemical composition, mechanical strength and creep properties

In Table 1 and 2 there are stated the results of analysis of chemical composition and mechanical properties of the most damaged bend.

Table 1 Chemical composition of the analyzed pipe bend [mass. %]

C	Mn	Si	P	S	Cr	Mo	V	Ni	Cu	Ti	Al	N	As	Sb	Sn
0.13	0.66	0.34	0.011	0.013	0.61	0.46	0.28	0.059	0.049	0.020	0.014	0.0130	0.006	0.002	0.007

Table 2 Mechanical properties of the evaluated pipe bend

$R_{p}0.2$	R_m	A	Z	KV+20 °C	KV+550 °C	$K_{\delta,0.2}$	FATT
MPa		%		J		$MPa \cdot m^{1/2}$	°C
294	486	26.0	66.7	26	60	132	+34

The results stated in Table 1 confirmed that the chemical composition corresponds well with the requirement of the material standard of steel grade 15 128 [4]; the material also shows relatively good metallurgical cleanness, i.e. low concentration of trace elements (Cu, Sn, As and Sb), which probably reflects the method of steel manufacturing process with minimum purchased metal scrap. The results of the analysis of mechanical properties show a decrease in strength combined with relatively favourable value of brittle-to-ductile transition temperature FATT. According to the material declaration, the bend should be supplied in the hardened and tempered state as the grade 15 128.9 with a minimum yield stress of 430 MPa. The measured value of the yield stress thus represents only 69 % of the minimum required value in the as-received state. It is, however, possible that still air cooling instead of accelerated cooling during heat treatment after bending has been used, which was common practice in 1970´s. If the previous statement is true, then the bend never had the properties of the grade 15 128.9 and the difference between the actual and as-received state (defined as $R_p0.2 \geq 330$ MPa) would not be so great and would reflect better the change of material strength due to the long-term operation at elevated temperature.

Hardness profile was also measured in the area of maximum damage of the bend either around the pipe circumference either through the wall thickness. Circumferential hardness measurement (HV 30) was carried out in three lines: close to the outer surface, in the middle of the wall thickness and close to the inner surface, in all cases with a distance 10 mm between the individual indentations. The results of the hardness measurement made in the outer and in the inner surface are shown in Fig. 2 and the local decrease in hardness in the area of defects on the outer surface is evident, while the hardness on the inner surface seems to be uniform around the whole pipe.

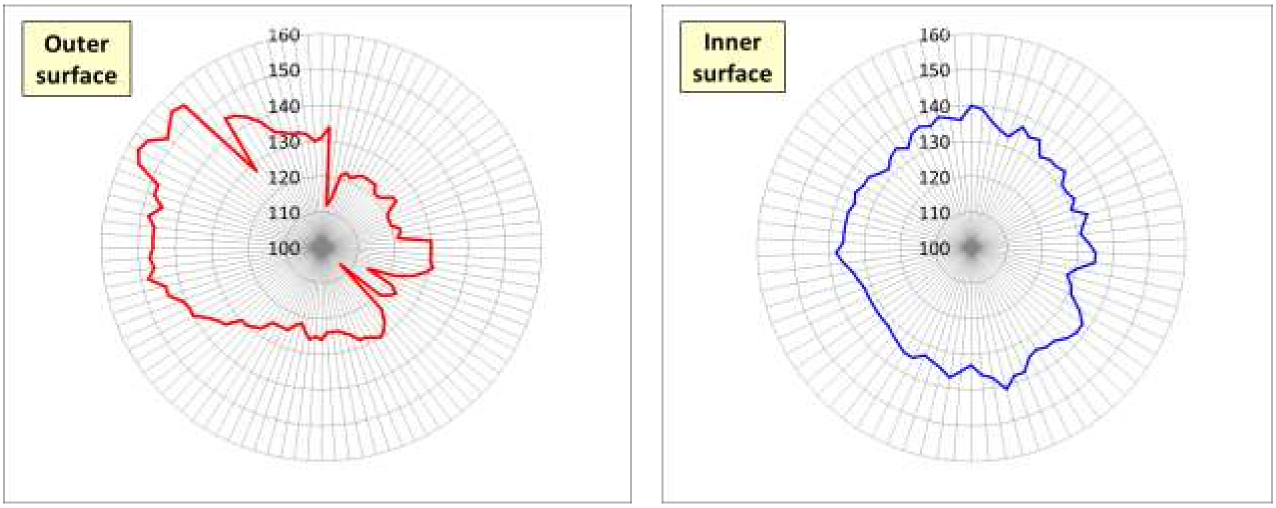

Fig. 2 Hardness profile HV 30 on the outer and inner surface of the pipe bend

In order to determine the actual creep characteristics of the pipe bend, creep rupture specimens were machined from the material close to the outer surface of the pipe in the area adjacent to the cracks. Creep testing program was performed at temperatures 550, 575 and 600 °C. Although so far completed creep tests do not reach long times to fracture, the results being at disposal already allow an evaluation of creep rupture strength for at least 10,000 hours. For comparison of the obtained creep testing results with the standardized data of the mean creep rupture strength R_u, the results of individual creep tests were converted into Larson-Miller parameter P_{LM} [5]. The results showed that the actual value of creep rupture strength (CRS) at 550 °C for 10,000 hours is 87 MPa, while the median standard value of R_u/550 °C/10 ^{4}h for the 15 128 steel grade equals 146 MPa and the median R_u/550 °C/10^4 h value of heats having yield point below 340 MPa drops down to 115 MPa. Thus, the actual CRS of the steam pipeline material is lower of about 40 % and 24 %, respectively, compared to the above stated values – see Fig. 3. Open symbols in this figure represent still running creep.

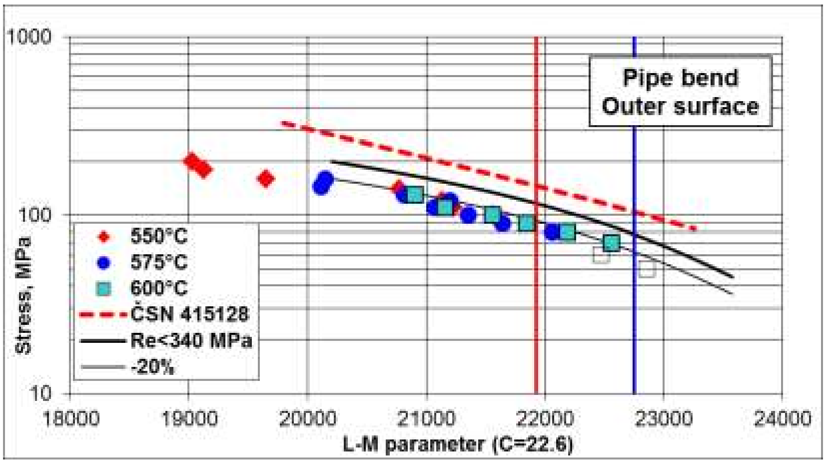

Fig. 3 Comparison of the results of creep tests with the values of CRS of the steel 15 128 for Re<340 MPa

2.2. Analysis of the microstructure and cavitation damage

Figure 4 illustrates the appearance of the outer surface of the pipe and the fracture surface of the principal crack in the defective area. These cracks were numerous and were oriented principally in the axial direction of the pipe bend. The appearance of the cracks confirmed their creep origin. The cracks originated on the outer surface and propagated in the intergranular manner from the outer surface of the tube in the direction approximately perpendicular to the surface of the pipe.

Crack surface was covered with the iron oxides on the outer surface of the pipe bend and during propagation towards the inner surface the branching of the cracks was observed, also covered with films of iron oxides. The total depth, in which the cracks propagated, was up to 7 mm below the outer surface, Fig. 5.

Fig. 4 Network of cracks on the outer pipe surface and fracture surface morphology

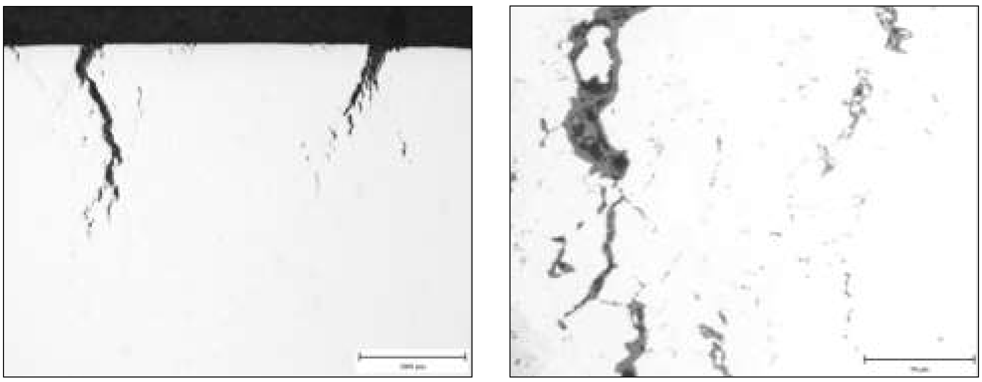

Fig. 5 Cracks partly fulfilled with oxidizes on the outer surface of the pipe

Microstructure in the area of creep cracks was fine-grained with tempered, ferritic-carbidic structure, in the inner surface of the pipe the microstructure had features of tempered bainite. Beneath the outer surface was observed significant cavitation damage and its frequency decreased towards the inner surface - Fig. 6. 5 mm below the outer surface were found both coarse and isolated cavities and also cavity chain with the length up to 139 microns. 10 mm or more from the surface there were observed only isolated cavities. With further increasing distance from the outer surface, the proportion of cavities and also their size decreased – Fig. 6.

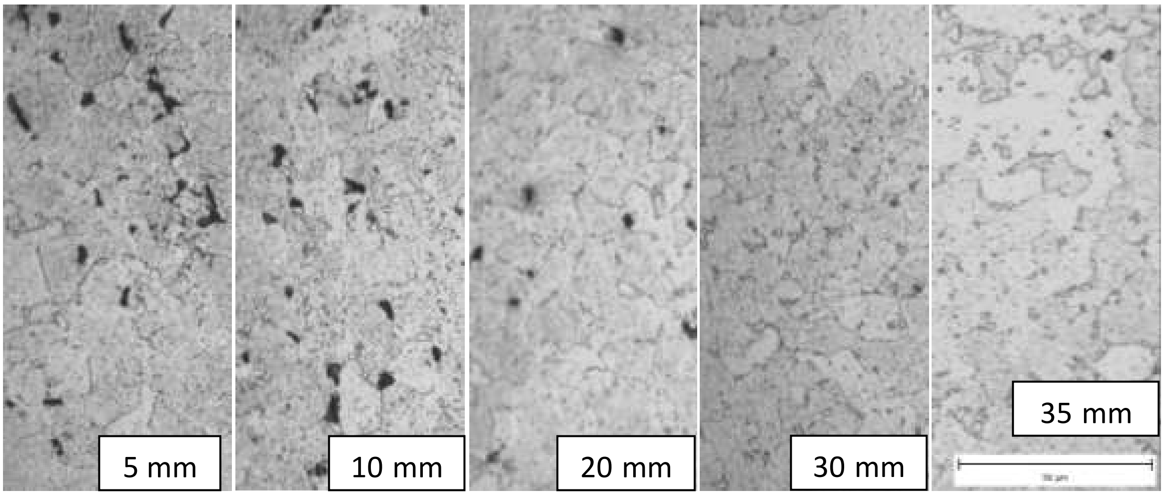

Fig. 6 Range of cavitation damage from the outer to the inner surface of the pipe bend

The microstructural analysis was then focused on evaluating the extent of cavitation damage through the thickness of the pipe wall as well as on its circumference. Evaluation of cavitation damage was made after method described in NORDTEST NT TR 302 [3] that combines the Neubauer classification [6], described and illustrated in detail in VGB TW 507 [1], with the access specified in NORDTEST NT TR 170 [2].

The extent of cavitation damage and its change depending on the distance from the outer surface of the pipe is documented in Table 3 for the maximum damage. In table 4 is shown the evaluation of cavitation damage for four locations around the pipe circumference in 90° rotation and corresponded to the drawn (0°) and compressed (180°) area and also the two neutral axes. From the results shown in these tables it is clear that extent of creep cavitation damage decreases as distance increases from the outer surface of the pipe to the inner surface as well as round the pipe circumference. Especially, with increasing distance from the outer towards the inner surface of the pipe the extent of cavitation damage changes very pronouncedly and drops down from the maximum *value 4b* to the *value 1*, which defines the microstructure without creep damage! This means that even in the occurrence of extensive microcracks on the outer surface, the inner surface is practically unaffected by creep damage!!

Table 3: Cavitation damage in area of defects through the wall thickness (according to NT TR 302)

Evaluated Area	Damage Type	Description of damage
At outer surface	5 / 4b	Macrocracks, extensive microcracks
Ca 5 mm from outer surface	2b / 3aK	Chains of cavities, little damage outside
Ca 10 mm from outer surface	2b	Isolated, more than 400 / mm^2
Ca 15 mm from outer surface	2b	Isolated, more than 400 / mm^2
Ca 20 mm from outer surface	2b	Isolated, more than 400 / mm^2
Ca 25 mm from outer surface	2a - 2b	Isolated, 100 - 400 / mm^2
Ca 30 mm from outer surface	2a	Isolated, 100 - 400 / mm^2
Ca 35 mm from outer surface	2a	Isolated, 100 - 400 / mm^2

Table 4: Cavitation damage in area of defects round the circumference (according to NT TR 302)

Evaluated Area	0°	90°	180°	270°
At outer surface	2b	1	2b	2b
Ca 10 mm from outer surface	2a	1	2b	2a
Ca 20 mm from outer surface	2a	1	2a	2a
Ca 30 mm from outer surface	1	1	1	1
Ca 40 mm from outer surface	-	-	1	1
At inner surface	1	1	1	1

2.3. Calculation of the critical crack size

Calculation of the redistribution of initial elastic stress during operation of the evaluated bend was carried out by finite element method for the actual geometry of the pipe bend and the material with lower strength and deformation properties (DMUV material with the default yield strength under 340 MPa) [7]. The calculations showed very rapid stress redistribution in the initial state and localization of maximum tangential stress at the outer surface of the pipe bend. It means that the initiation of creep cracks can be expected on the outer surface and there is, therefore, a good chance to find them during the regular inspections – see Fig. 7.

The critical crack depth for the initiation of the final fracture was determined for the actual values of the yield strength, ultimate strength and fracture toughness of the bend at 550 °C. The calculation was made for a considerable length of longitudinal cracks extending from the inner and outer surface of the bend depending on the risk of failure. Even for a low probability of fracture (Pf = 0.001) is the ratio of critical crack depth to the actual minimum wall thickness greater than 0.5, which means that the only cracks with a depth exceeding one half of the wall thickness can be regarded as dangerous – see Fig. 8. This result supports optimism about the safe operation of the steam pipes, as we can expect that the crack would be detected before it grows to this length.

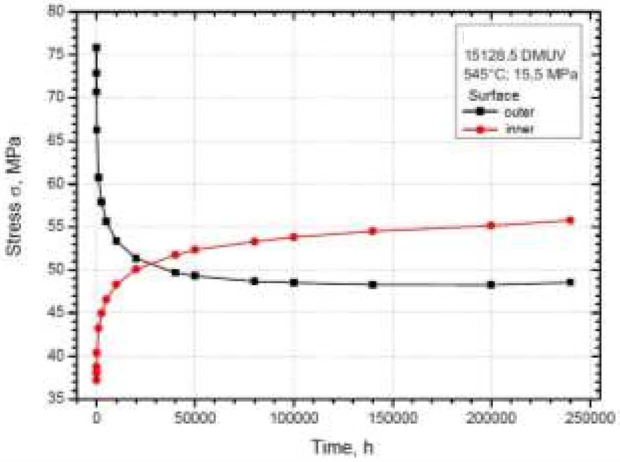

Fig. 7 Redistribution elastic stress during bending operation

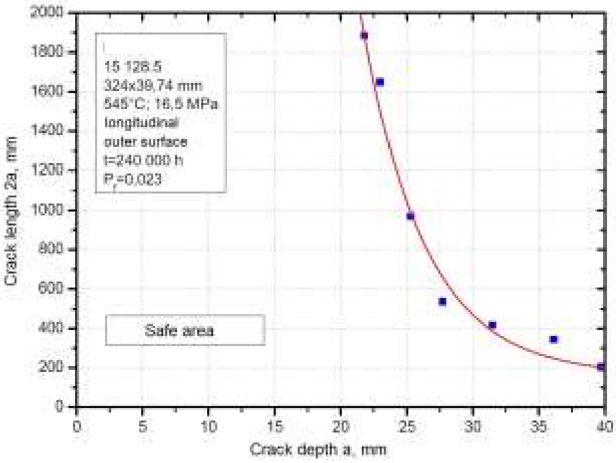

Fig. 8 Relation between depth and length of the critical crack for sudden fracture

CONCLUSION

Considerable inhomogeneity detected in the pipe bending of 200 MW boiler demonstrates and confirms what was well-known about the creep damage of the steel grade 15 128 and all the group of low-alloy Cr-Mo-V steels. Although creep damage reaches the value 5 on the outside surface of the pipe bend and 4b in the regions between macrocracks, below this surface region the density of cavities decreases from about 2,000 / mm^2 to approximately 150 / mm^2. Similar creep damage heterogeneity was also observed around the pipe circumference. In the compression area of the bend the degree of creep damage reached only 1, i.e. again virtually free of cavities (<150 / mm^2). Heterogeneity of the creep damage and the fact that the creep crack formation occurs on the outer surface of the bend and near the outer fibres is very favourable in terms of searching the maximum creep damage, because it is a region which is usually well accessible for diagnostic investigation.

The exhausted creep life of the steam pipe bend was reflected also by the mechanical properties and to some extent even by notch toughness. Hardness measured in the area of cracks on the outer surface only slightly overcame 100 HV, outside cracks and towards the inner surface then reached of about 135 HV. Also, the yield strength at room temperature did not exceed 300 MPa, although the same decrease was not detected in the tensile strength, which value was close to the standardized minimum of 15128.5 steel. In the time of bends manufacturing it was not usual to apply rapid (water) cooling from the austenizing temperature, which is necessary in order to obtain steel grade 15128.9 with higher strength as well as creep resistance.

The fracture toughness at temperatures close to the working temperature (550 °C) is not low enough to cause risk of sudden brittle fracture. It is reasonable to assume that the creep cracks will grow slowly and by stable growth, which increases the chance of finding them early during the routine diagnostic tests, particularly if the critical depth of the creep crack is greater than half of the thickness of the pipe wall. This gives a real chance to move the limit criteria considering the life of steam pipes from the occurrence of chains of cavities to the presence of microcracks.

ACKNOWLEDGEMENTS

This paper was created in the frame of the Project No. LO1203 "Regional Materials Science and Technology Centre-Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic.

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