CREEP DAMAGE OF LOW-ALLOY STEELS AFTER LONG-TERM EXPOSURE AND ITS EVALUATION BY REPLICA METHOD

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Abstract

The intended operation time prolongation of the key components of fossil-fuelled power plants working in the creep conditions over 200,000 or even 250,000 hours (far beyond their original design lifetime) must be accompanied by thorough and extensive monitoring of the current material state and particularly creep damage. The extent of cavitation damage is routinely tested in-situ by using replica method and its quantification is based on a practice stated in VGB-TW 507, NORDTEST NT TR 170 or NORDTEST NT TR 302 that further develop the original Neubauer's classification. Although the evaluation of cavitation damage based on the measurement of the number of cavities and/or creep micro-cracks is a routine activity, what is still in question is the depth of the damaged area and the corresponding material properties through the wall thickness.

Mutual correspondence between the creep damage evaluation performed in accordance with NORDTEST NT TR 302 and VGB TW 507 was carried out in a pipe bend made of a low-alloy 0.5Cr-0.5Mo-0.3V steel which was creep exposed at 525-540 °C for more than 225,000 hours and the relation between creep damage at the outer surface of the pipe bend (as a typical result of replica testing) and mechanical properties of the whole pipe bend were discussed in the paper with reference to the residual life assessment.

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

1. INTRODUCTION

Many of the fossil-fuelled 110 MW and 200 MW boilers in the Czech Republic are at present operated after their design life. This is especially the case of steam pipelines (some of them have been operating for nearly 300,000 hours), while the economizer, super-heater and re-heater tubes have been already changed. The question of prolonged lifetime of steam pipelines is therefore of great urgency not only due to the economic impact but also with regard to the safety reasons.

In order to access the safe life or time period for repeated assessment of the material properties of high temperature components, many methods based on evaluation of cavitation or cavitation damage are used around the world. The correct interpretation of analyzed creep cavitation damage requires evaluation of the extent of cavitation damage according to clearly defined and generally accepted damage scale.

In the present paper the attention will be paid to the comparison of the cavitation damage classification of a pipe bend made of low-alloy 0.5Cr-0.5Mo-0.3V steel and creep exposed at 525-540 °C for more than 225,000 hours and the correlation between cavitation damage and other mechanical properties of the respective pipe bend.

2. METHODS OF QUANTIFICATION OF CREEP CAVITATION DAMAGE

Several rules or enterprise standards are currently available worldwide describing the guidelines for analysis and assessment of the extent of creep damage, namely VGB TW-507 [1] (nowadays supplemented with VGB S-517-00 [2], NORDTEST NT TR 170 [3], NORDTEST NT TR 302 [4] and others. Although all of them are based on replica testing and originate in the same Neubauer´s evaluation method of creep cavitation damage [5], the first two guidelines provide namely photographs of reference microstructures of the mostly used high-temperature steel grades in various states of cavitation damage and the criteria for their evaluation are rather vague, the second two of Scandinavian origin provide more exact rules for classification of cavitation damage and strictly quantify the extent of cavitation in the respective damage classes. The German guideline VGB TW-507 [1] (and now VGB S-517 [2]) does not state explicitly and in detail how each class of damage is defined, but refers only to the Neubauer´s division of damage classes, as shown in **Table 1**.

Table 1 Description of Neubauer damage classes as used in VGB TW-507

Assessment class	Description of damage
0	As received, without creep exposure
1	Creep exposed, without cavities
2a	Advances creep exposure, isolated cavities
2b	Numerous cavities without preferred orientation
3a	Numerous cavities with directional orientation
3b	Chains of cavities or grain boundary separation
4	Microcracks
5	Macroscopic cracks

The VGB TW-507 shows a complete set of micrographs in the as received and after various classes of creep cavitation damage for a wide range of heat resistant materials, and therefore it is used or at least referred to by a large group of professionals dealing with residual life assessment not only in Germany but also in the neighboring countries, including the Czech Republic.

On the other hand, in the NORDTEST NT TR 170 the reference micrographs of the creep cavity damage are stated only for selected conventional low-alloy steels 14 MoV 6-3 (0.5 Cr-0.5 Mo-0.25 V), 13 CrMo 4-4 (1 Cr-0.5 Mo) and 10 CrMo 9-10 (2.25 Cr-1 Mo) Micrographs were selected from a large number of replicas, all taken from power plant components after they were in operation for more than 80,000 hours and mostly from different welding areas. Optical (and also scanning electron) micrographs show the extent of damage in each assessment class of cavitation damage in magnification that is commonly used in replica inspection (200, 500, and 1000x). The principal difference between both methods was more detailed assessment class division in NORDTEST NT TR 170 and mainly quantification of cavitation damage in all classes given in the NORDTEST [3]. The comparison between the cavitation damage classification according to NORDTEST NT TR 170 and VGB TW-507 is shown in **Table 2**.

Table 2 Relation of cavitation damage evaluation between VGB TW-507 and NORDTEST NT TR 170

<table>
<tr><th>Damage scale</th><th>No damage</th><th>No cavitation (exposed)</th><th colspan="3">Isolated cavitation</th><th colspan="3">Oriented cavitation</th><th colspan="3">Microcracks</th><th>Macrocracks</th></tr>
<tr><td>NT TR 170</td><td>0</td><td>1</td><td>2.1</td><td>2.2</td><td>2.3</td><td>3.1B</td><td>3.2B</td><td>3.3B</td><td>4.1</td><td>4.2</td><td>4.3</td><td>5</td></tr>
<tr><td>VGB TW-507</td><td>0</td><td>1</td><td>2a</td><td colspan="2">2b</td><td>3a</td><td colspan="2">3b</td><td colspan="3">4</td><td>5</td></tr>
</table>

Mutual correspondence between NORDTEST NT TR 170 and VGB TW-507 damage scales was then performed in the NORDTEST NT TR 302 [4] and this comparison resulted in a table with a new cavitation damage assessment criteria especially for Class 2 and 3, see **Table 3**.

Table 3 Definition of creep cavitation damage according to NORDTEST NT TR 302

Class	Damage type	Definition of damage		Remark
0	No damage (new material)	N≤ 100 cavities/mm^2 with a size ≥0.5µm		1)
1	No cavitation (thermal exposure)	N≤ 100 cavities/mm^2 with a size ≥0.5µm		1)
2	Isolated cavities	Cavities without chainlike formation or grain boundary separation		1)
2a	*- small amount*	*100 ≤ N ≤400 cavities/mm^2*		
2b	*- extensive*	*N > 400 cavities/mm^2*		
3	Oriented cavitation	Cavity chains/gb separations (max. 3 grains or 100 µm)		1), 2), 3)
		Type K	Type C	
3a	*- small amount*	*50≤L_{cmax}≤200 µm*	*400≤N≤1600 cavities/mm^2*	
3b	*- extensive*	*L_{cmax}>200 µm*	*N>1600 cavities/mm^2*	
4	Microcracks	Cracks with (3x grain size or 100 µm) < L_{max} ≤ 2 mm		3), 4), 5)
4a	*- small amount*	*Max (3x grain size or 100 µm)< L_{max} ≤ 400 µm*		
4b	*- extensive*	*400 µm < L_{max} ≤ 2mm*		
5	Macrocracks	Cracks detectable in conventional NDT, L_{max} > 2mm		4), 5)

1) N = area density of cavities on actual sample surface (cavities/mm^2)

2) Note that

type **K** - damage refers to cases with little damage outside the main lines of damage;

type **C** damage refers to cases with distributed cavity formations;

- at low levels of orientated cavitation (class 3a lower limit) types K and C may be inseparable;

- cavity chain = formation with several cavities on a grain boundary extending to adjacent grains

- gb = grain boundary

3) L_{cmax} = total summed maximum length of continuous cavity lines, each at least 50 µm in length and fulfilling the line density requirement of at least 100 cavities / mm of the grain boundary line under consideration, in an image with an area of 100 cm^2 at 500x magnification.

4) It is recommended that also the damage outside the cracks is indicated: e.g. 4b / 1; 4b / 3bC or 5 / 4a / 3aK

5) L_{max} = maximum length of the cracks; two cracks are counted as one, if their distance is less that the length of the shorter crack; the total length = combined cracks and ligaments projected in the main crack direction.

The next chapter will describe the method and results of creep cavitation damage evaluation of a pipe bend made of low-alloy 0.5Cr-0.5Mo-0.3V steel after exposure at 525 - 540 °C for more than 225,000 hours. The analysis of cavitation damage was performed according the both methods described here and some interesting difference between them appeared.

3. ANALYSIS OF CREEP CAVITATION DAMAGE AND MATERIAL PROPERTIES OF A STEAM PIPELINE BEND

The metallographic analysis performed “in-situ” on the pipe bend by using replica method revealed the extended creep cavitation damage in two places about 150 mm away on the extrados of the pipe bend, approximately in the centre of the bend. The piece was then replaced and the detailed microstructural analysis was made on several metallographic samples prepared from one of the damaged places in various depths parallel to the outer surface. After etching, the revealed microstructure was heavily tempered and formed a mixture of ferrite and carbides. The evaluation of the degree of the original ferritic-perlite and/or ferritic-bainitic microstructure decomposition was made by using classification for low-alloy creep resistant steels [6, 7]. According to this classification, the microstructure of the sample was evaluated as grade D., i. e. advanced spheroidization of the carbides and secondary carbides reprecipitated on the grain boundaries.

Analysis of cavitation damage confirmed the results of replica testing and numerous chains of cavities of length not exceeding 200 µm were observed both on the outer surface and under it in depth 5 mm, see **Figures 1** and **2**. At a depth of 10 mm, chains of cavities were observed mainly locally and isolated cavities were detected in small amounts, see **Figure 3a)**. At a depth of 15 mm below the outer surface of the pipe bend, the number of cavities was further reduced, the chains of cavities were recorded only sporadically and the presence of isolated cavities was relatively limited, too, see **Figure 3b)**. Finally, at a depth of 20 mm, the number of cavities was further reduced and the only isolated cavities were recorded, see **Figure 4**.

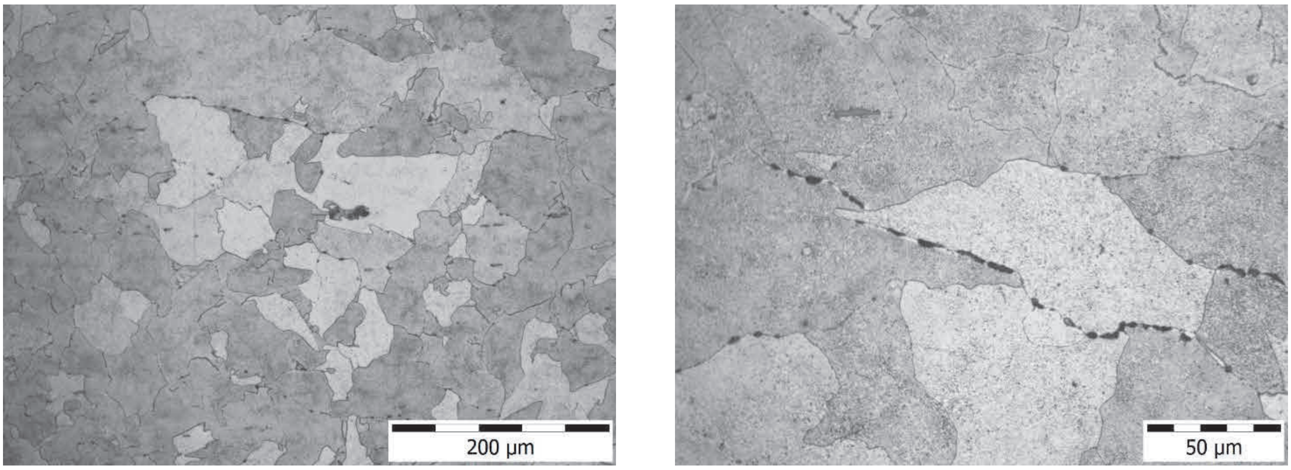

Figure 1 Cavitation damage on the outer surface of the steam pipe bend (overall view and detail)

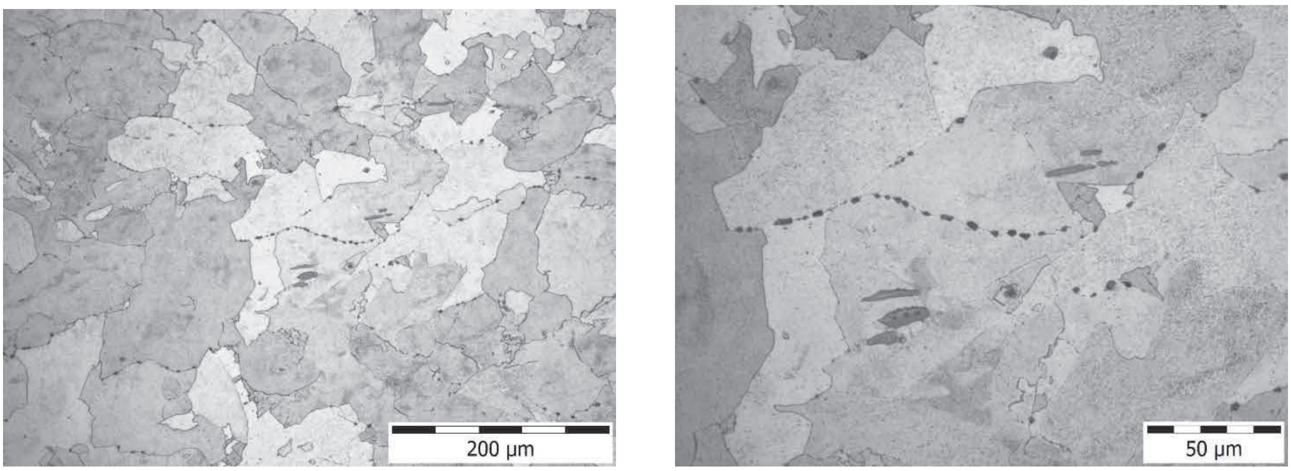

Figure 2 Cavitation damage 5 mm under the outer surface of the steam pipe bend (overall view and detail)

All results of the evaluation of creep damage performed according to the VGB-TW 507 as well as the NORDTEST NT TR 302 guidelines are summarized in **Table 3** complemented by the results of hardness measurements (HV10) made in the same places where cavitation damage was assessed.

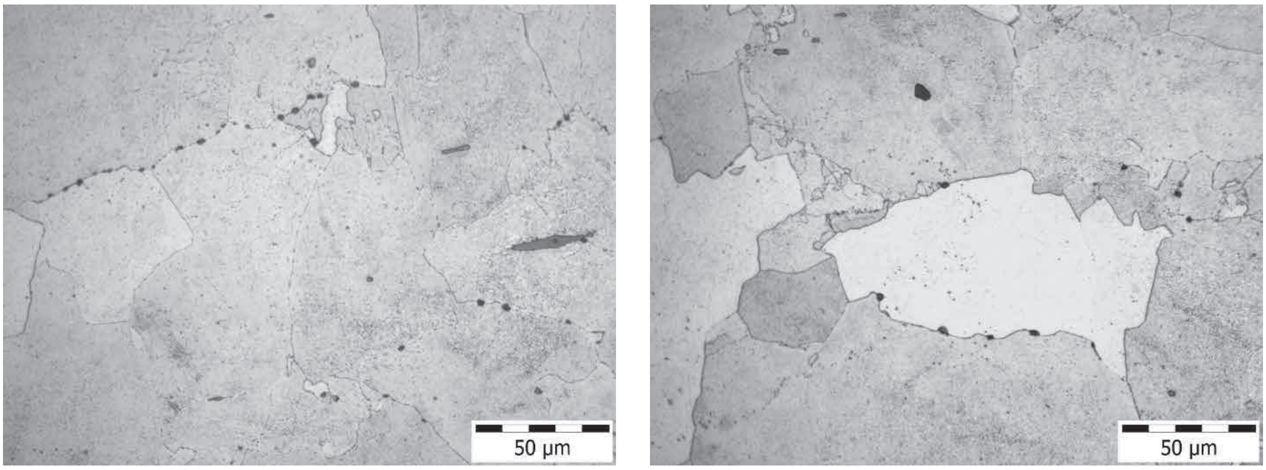

Figure 3 Cavitation damage 10 mm (a) and 15 mm (b) under the outer surface of the steam pipe bend

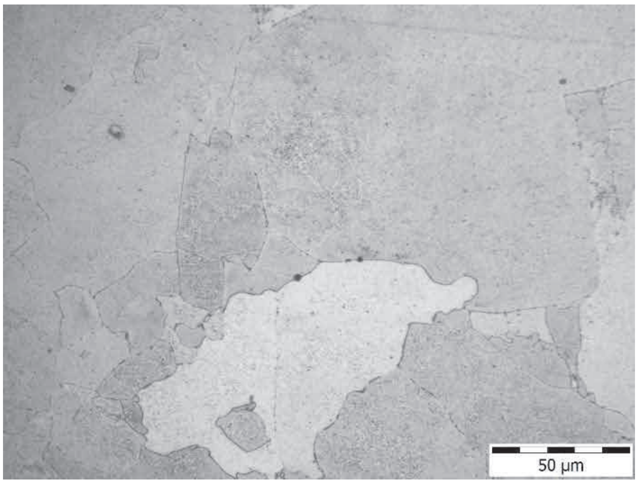

Figure 4 Isolated cavities 20 mm under the outer surface of the steam pipe bend

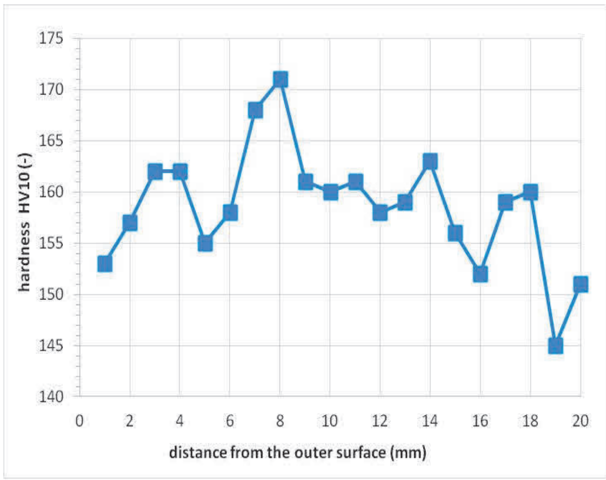

Figure 5 Hardness profile through the wall thickness

Table 3 Evaluation of creep damage and hardness measurements at different depths under the outer surface of the pipe bend

Sample	VGB-TW-507	NORDTEST NT TR 302	Hardness HV10
Outer surface	3b	3a	153
5 mm under outer surface	3b	3a	163
10 mm under outer surface	2a, locally 3a	2a, locally 3a	157
15 mm under outer surface	2a, rarely 3a	2a, rarely 3a	150
20 mm under outer surface	2a	2a	148

Additional hardness measurements through the wall thickness of the pipe bend were performed with the aim to find out how the cavitation damage affects mechanical properties of material. Hardness (HV10) was measured with a distance between indentations approximately 1 mm, conventional tensile tests and small punch tests samples were prepared as close to the outer surface as possible. The results showed slight hardness increase from the outer surface to 8 mm under the surface and then hardness decline towards inner surface, which is surprising in context of cavitation damage, more or less fluently decreased from the outer to inner pipe surface.

CONCLUSION

NORDTEST NT TR 302 uses the quantitative approach to determine creep cavitation damage classes, which makes this method more objective making the observation results more objectively than the VGB TW 507, which is based primarily on a subjective visual evaluation and comparison of reference images of structures. NORDTEST NT TR 302 is, on the other hand, based on measurements and calculations of both the cavity area and the lengths, or the total length of cavity chains or micro-cracks. The practical consequence of such a different approach is the difference in the assessment of the cavitation damage classes stated in **Table 3**, when in the case of NORDTEST NT TR 302 the resulting degree of cavitation damage is lower than that of the VGB TW 507 (3a versus 3b). Creep cavitation damage evaluated according to NORDTEST NT TR 302, is therefore more objective control, which is less influenced by the subjective opinion of the evaluator, but the same evaluation can be expected at any time and by a third party. This objectification led, for example, to the above described situation, when evaluation according to the VGB TW 507 based on comparison of the sample microstructure with the reference images of 14 MoV 6 3 resulted in damage class 3b, however the total length of the chains of cavities neither exceeded 200 μm nor was the number of individual cavities higher than 1600/mm^{2,} which is a prerequisite for class 3b.

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