CREEP CAVITATION BEHAVIOUR OF P91/P92 STEELS DURING LONG-TERM CREEP TESTS

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Abstract

The presence and importance of cavitation damage and fracture during creep of Cr-Mo-V creep resistant steels (including martensitic grades) increases with increasing temperature and time to fracture, and at the same time, a decrease in fracture elongation can also be observed. In the case of uniaxial creep tests, the area and distance from the fracture line where the cavitation can be detected while its intensity gradually decreases also increases.

The creep cavitation behaviour of P91 and P92 steels was monitored in a series of creep tests performed in the temperature range of 575 to 625 °C and with a time to fracture of up to 35,000 hours. The extent of cavitation damage was assessed, depending on the distance from the fracture line, according to the procedure according to NORDTEST TR 302, in which classification into individual damage classes is based on a quantitative assessment of the number of cavities, or length of chains of cavities and/or microcracks.

Keywords: Creep, cavitation damage, martensitic steels, NORDTEST TR 302

1. INTRODUCTION

Fossil-fuelled, mainly ultra-supercritical (USC) blocks, were built worldwide during the last decade of the 20th century and later and at present they are operated around the half of the design life. Therefore, there is the demand to start regular inspections and to learn the actual material condition as well as to estimate the expected remanent life of the key component of the pressure system of these boilers. The adequate and well described material condition is of great importance not only due to the possible economic impact but also with regard to the safety reasons. Key components of the pressure system of a boiler represent, among others, pipelines and header that were in USC boilers made of advanced chromium modified steels, predominantly martensitic grades P91 and P92.

Creep cavitation damage usually limits the life of a component in the creep exposed part of a boiler. The appearance and growth of individual cavities, forming of strings of cavities, their joining into microcracks and macrocracks represents the typical life course of such a component ending with the final fracture. The observed extent of cavitation can be on the other hand used to indicate the damage status during the regular service inspections. When the creep behaviour of the material is well-known, these inspections can be limited to a very small fraction and the residual lifetime and/or the safe inspection periods can be set according to the existing guidelines [1,2]. However, such knowledge or experience is not available for new steels, and especially modern martensitic chromium modified steels that deviate from the foreseen damage evolution, and, among others, they show significant decrease in creep ductility with increasing temperature and time to rupture. At present, there are published mainly the results of premature failure during service particularly due to improper microstructure [3,4].

In the present paper the attention will be paid to the extent of cavitation damage in P91 and P92 classified on the stress rupture tests performed at temperature 600 °C and various time to rupture.

2. EXPRIMENTAL MATERIAL AND METHOD OF CREEP CAVITATION DAMAGE ASSESSMENT

Stress rupture tests were made on a steam pipe ø 605 mm x 35 mm made of P 91 steel and a seam pipe ø 530 mm x 80 mm made of P 92 steel and both steels were tested in the as-received state, i.e. after normalizing and tempering. The chemical composition of both pipes, including the nominal values specified in EN 10216-2 [5], is stated in **Table 1**, mechanical properties including yield and tensile stress, elongation and reduction of area (R. A.) as well as the most representative creep rupture strength at 600 °C after 100,000 hours ($R_{uT}10^5/600$) calculated from the results of the experimental program are stated in **Table 2**, again with the standardized values specified in the material standard [5]. The results of stress rupture tests of the individual pipes are illustrated in **Figure 1** and **Figure 2** as the stress-Larson-Miller parameter dependence [$P_{LM} = T(C+logt)$] with Larson-Miller constant C calculated by the method of least squares from the stress rupture data stated in the material standard. The individual test temperatures are there distinguished by different symbols and colours, while empty symbols indicate still running tests. In total, more than 315,000 hours have been tested so far on both tubes. In these figures there are also marked by numbers the test specimens used for the development of creep cavitation damage in this paper.

Table 1 Chemical composition of steel**s** P91 and P92 (wt %)

Steel	C	Mn	Si	P	S	Cr	Mo	V	Nb	W	Ni	Al	N	B
P91	0.10	0.42	0.29	0.012	0.004	8.29	0.93	0.19	0.079	0.09	0.21	0.002	0.052	-
P92	0.10	0.41	0.20	0.013	0.004	8.74	0.48	0.18	0.050	1.66	0.21	0.001	0.056	0.0020
P91 (EN)	0.08-0.12	0.30-0.60	0.20-0.50	max. 0.020	max. 0.010	8.50-9.50	0.85-1.05	0.18-0.25	0.06-0.10	-	max. 0.40	max. 0.020	0.003-0.007	-
P92 (EN)	0.07-0.13	0.30-0.60	max. 0.50	max. 0.020	max. 0.010	8.50-9.50	0.30-0.60	0.15-0.25	0.04-0.09	1.50-2.00	max. 0.40	max. 0.020	0.003-0.009	0.001-0.006

Table 2 Mechanical properties of steels P91 and P92

Steel	$R_{p0.2}$ (MPa)	R_m (MPa)	Elongation (%)	R. A. (%)	KV (J)	$R_{uT}10^5/600$ (MPa)
P91	596	731	23.3	73.7	205	87
P92	484	646	26.6	72.2	176	108
P91 (EN)	min. 450	630-830	min. 19	-	27	90
P92 (EN)	min. 440	620-850	min. 19	-	27	113

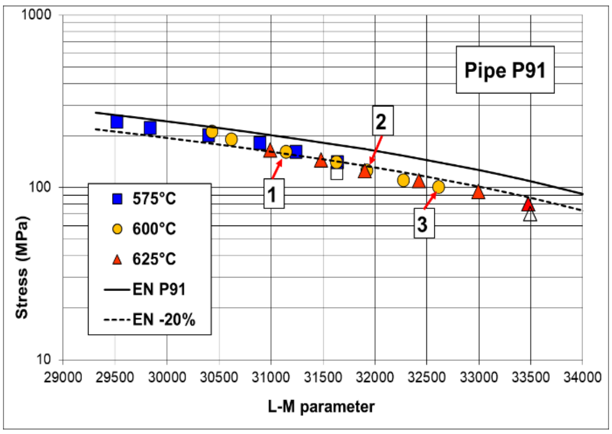

Figure 1 Results of stress rupture tests of a pipe made of P91 steel

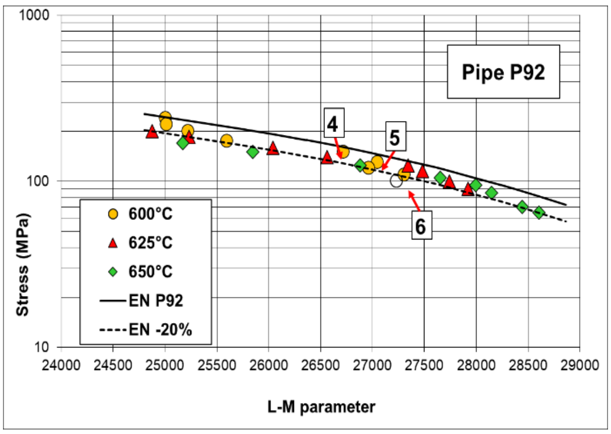

Figure 2 Results of stress rupture tests of a pipe made of P92 steel

From several guidelines that are currently available worldwide and describe the methods how to analyse and assess the extent of creep damage, all of them building on the previous approaches and based on the original Neubauer´s classification [6], the most detailed is NORDTEST TR 302 with countable procedure for assigning a result of analysis to a given level of cavitation damage, see **Table 3** [1]. Although this procedure is designed mainly for the evaluation of replicas, it can of course also be applied to bulk metallographic samples.

Table 3 Classification of creep cavitation damage according to NORDTEST TR 302 [1]

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. 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 analysis of creep cavitation damage was performed on the selected stress rupture tests after rupture. The temperature 600 °C was selected as the reference temperature of both steels and three test specimens were used in both cases covering times to rupture from about 1,000 hours up to more than 30,000 hours. The testing parameters of them are summarised in **Table 4** and the positions of these test specimens among others is highlighted in **Figure 1** and **Figure 2** by a circle and the number of the individual test. Cavitation damage was analysed on the longitudinal sections of test specimens as close as possible to the rupture line and then at distances 3-, 5-, 10- and 20-mm. Metallographic specimens were prepared by standard preparation technique of grinding and repeated polishing and etching and evaluated by using optical microscope. Cavitation damage was classified according to the guideline NORDTEST TR 302 stated above in **Table 3**.

Table 4 Results of stress rupture tests used for cavitation damage analysis

Steel	Sample	Temperature (°C)	Stress (MPa)	Time to rupture (h)	Elongation (%)	R. A. (%)
P91	**1**	600	160	516	31.4	76.9
	2	600	125	4,014	41.6	85.5
	3	600	100	24,890	13.4	24.4
P92	**4**	600	150	6,442	13.5	37.5
	5	600	130	15,385	8.2	12.7
	6	600	110	30,288	9.2	7.7

3. RESULTS OF CAVITATION DAMAGE ASSESSMENT

Etching revealed in all samples tempered martensitic microstructure. The extent of cavitation damage covered nearly all the classes specified in **Table 3** and analysis confirmed the anticipated increasing extent and range of cavitation damage with increasing temperature and time to fracture, as well as the fact that cavitation decreases rapidly with increasing distance from the fracture line. Such a heterogeneity of cavitation damage is a typical feature of creep damage in precipitation strengthened Cr-Mo-V steels. The overall view of the longitudinal sections of all samples showing namely the different and still lower necking in the rupture area with increasing times to rupture is shown in **Figures 3** and **4**.

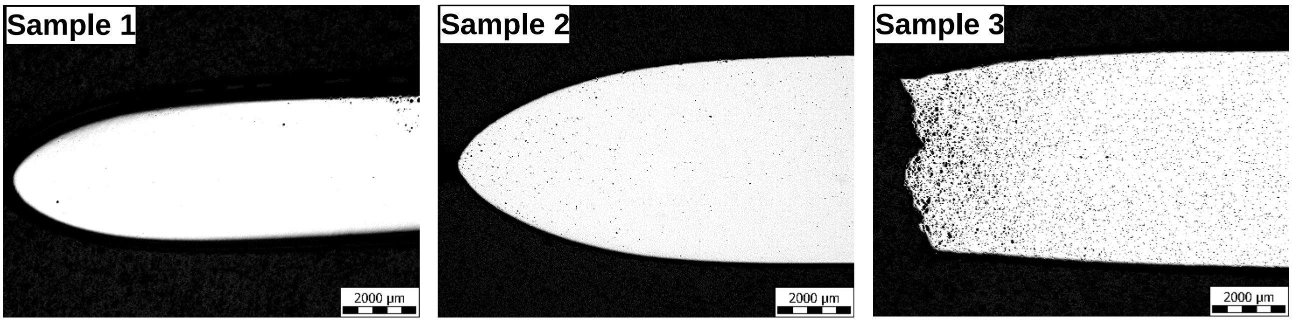

Figure 3 Cavitation and necking of the rupture area of stress rupture tests of steel P91

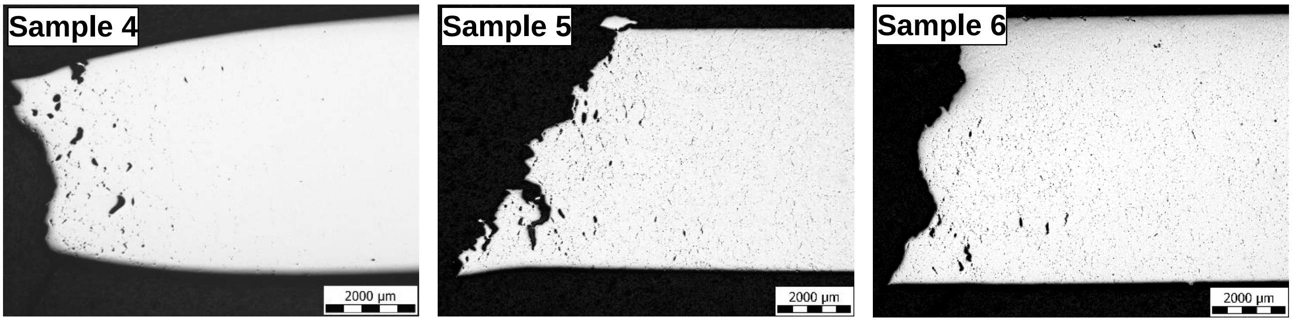

Figure 4 Cavitation and necking of the rupture area of stress rupture tests of steel P92

The cavitation damage was in all studied cases the heaviest on the fracture line and immediately below it. However, even as close to the fracture line as 3 mm (and farther) cavitation in the shortest times to rupture in both studied steels practically disappeared and only isolated cavities (class 2a) were detected. With increasing times to rupture cavitation spread and affected areas farther from the fracture line and in tests with the longest times to rupture extensive cavitation was found along the whole gauge length of the test specimens. All results of the evaluation of creep damage performed in accordance to the NORDTEST TR 302 are summarized in **Table 5**. Surprising is the absence of cavitation damage in sample 1 (steel P91, 516 h) on the rupture line, but the time to rupture of this test was so short that ductile fracture with intensive necking occurred without significant development of cavitation. Fracture plasticity (reduction of area) is greater in steel P91 then P92, while the steel P92 is heavily cavitated in comparable samples, as can be seen in detail in **Figures 5** to **8**.

Table 5 Evaluation of creep damage at different depths under the fracture line

Steel	Sample	Fracture line	3 mm	5 mm	10 mm	20 mm
P91	**1**	1	1	2a	2a	2a
	2	Type C/3a	2a	2a	2a	1
	3	4a	Type C/3a	Type C/3a	2a	2a
P92	**4**	4a			2a	2a (1)
	5	4a	4a	4a	Type K/3a	Type K/3a
	6	4a	4a	4a	Type K/3a	Type C/3a

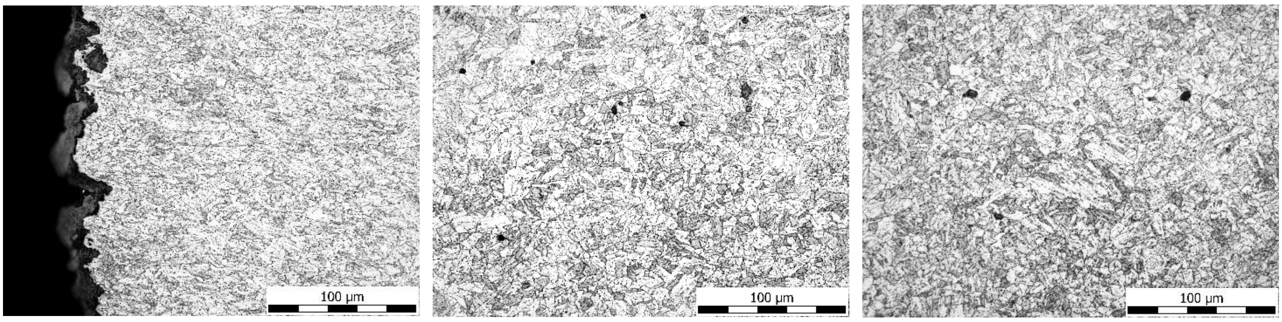

Figure 5 Sample 1 (P91, 516 h) - cavitation damage: rupture line (left), 5 mm (centre), 10 mm (right) away

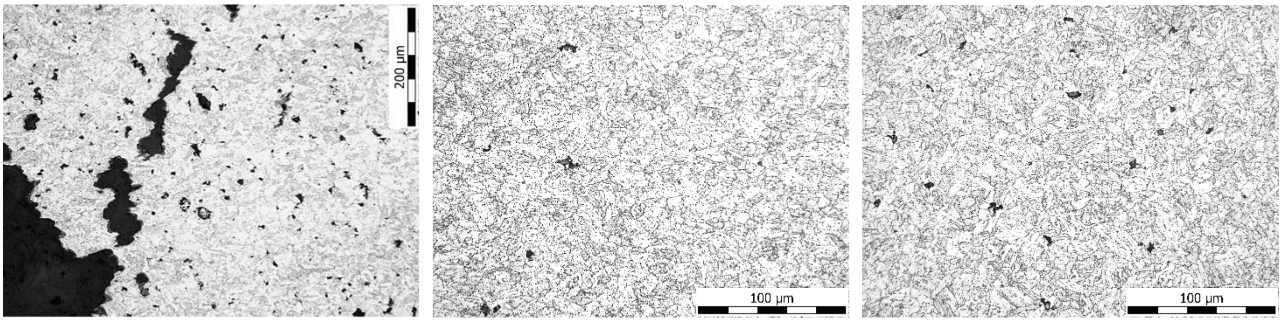

Figure 6 Sample 3 (P91, 24,890 h) - cavitation damage: rupture line (left), 5 mm (centre), 10 mm (right) away

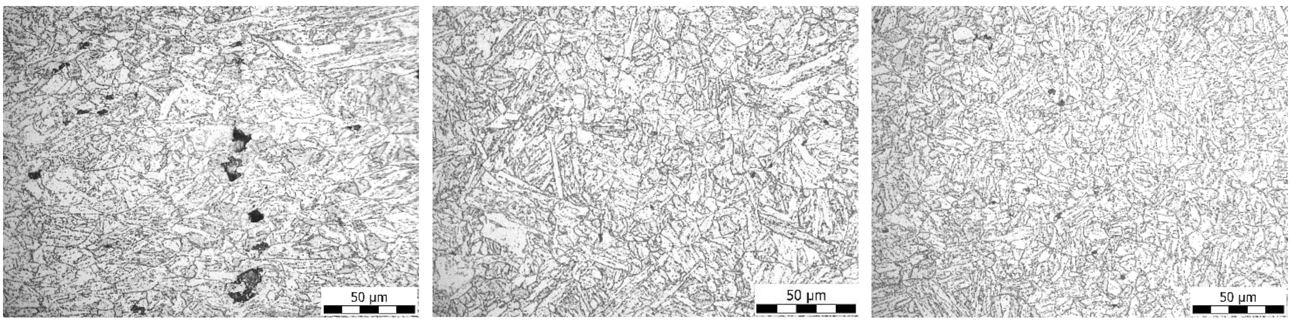

Figure 7 Sample 4 (P92, 6,442 h) - cavitation damage: rupture line (left), 5 mm (centre), 10 mm (right) away

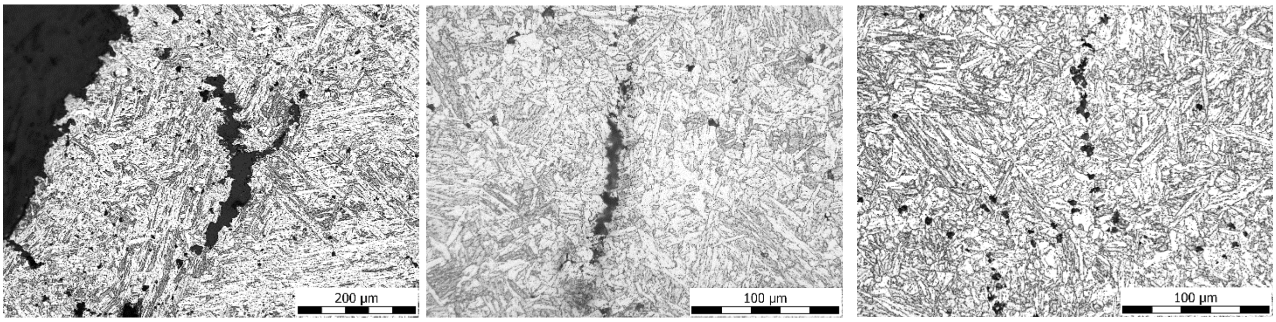

Figure 8 Sample 6 (P92, 30,288 h) - cavitation damage: rupture line (left), 5 mm (centre), 10 mm (right) away

4. CONCLUSION

Metallographic analysis of cavitation damage performed on broken stress rupture tests made of P91 and P92 steels and creep exposed at 600 °C up to 30,000 hours confirmed that:

- in both steels with increasing time to rupture the fracture ductility decreases and especially the reduction of area,
- most cavitation damage is concentrated close to the final rupture, while the rest is virtually unaffected; this is especially true for lower temperatures and short times to rupture,
- with increasing time to rupture increases also the area affected by cavitation and the longer is time to rupture the more severe cavitation damage can be found farther from the rupture,
- cavitation damage in these steels can be reliably classified by using guideline NORDTEST TR 302.

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