THE FAILURE ANALYSIS OF A PIPELINE BEND MADE OF 16Mo3 STEEL

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Abstract

Steel 16Mo3 (P1 according to ASTM) represents still a popular material used in waterwalls, pipelines and other components of steam power plant boilers operating at temperature up to 530 °C. However, the absence of other alloying elements (especially chromium) reduces the long-term structural stability of this steel especially at temperatures higher than 450 °C. The paper describes the results of an analysis of a pipeline bend that burst after nearly 180,000 hours of operation. The complex analysis of material properties and microstructure revealed the extensive graphitization, although mechanical strength, plasticity as well as notch toughness were affected only negligibly. Particles of graphite were randomly distributed in the microstructure and heavy cavitation damage was detected namely close to the fracture surface. Analysis of operation data then showed that the temperature in this part of the steam pipeline was higher due to the changes in the fuel mix and exceeded the maximum 470 °C recommended for the steel 16Mo3 just in order to avoid the danger of massive graphitization

Keywords: 16Mo3 steel; steam pipeline; creep failure; graphitization; material properties

1. INTRODUCTION

The absence of strong carbide forming elements (typically Cr, Mo, V, Nb) is the principal reason why carbon-manganese and molybdenum steels are susceptible to cementite decomposition into graphite during long-term exposure at higher temperatures. Graphitization was found in C-Mo steels with up to 1 % Mo and without another strong carbide forming element, that could retard decomposition of cementite and formation of graphite. The addition of about 0.7 % chromium eliminates graphitization in low-alloy steels [1].

In general, some steels are much more susceptible to graphitization than others, but exactly what causes some steels to graphitize while others are resistant is still not well understood. Long time was accepted that silicon and aluminium that both do not form carbides in steel promote graphitization, but it has been shown that, although they can facilitate the nucleation of graphite particles, the total influence of Al and Si on graphitization is negligible [2]. Nevertheless, there still exists a rule not to overcome the total Al content above 0.015 wt.% in a steel for use at elevated temperature. Temperature has an important effect and below 430 °C the rate of graphitization is extremely slow for C-Mn and/or C-Mo steels. There are two general types of graphitization:

- random graphitization in which the graphite nodules are distributed randomly throughout the steel. This type of graphitization may lower the room-temperature tensile strength but usually it does not lower the creep resistance.
- chains of graphite nodules. This form of graphitization can significantly increase the risk of brittle fracture along this chain and thus reduce load bearing capacity. This form of graphitization (called also eyebrow graphitization) is very often observed in the heat affected zone of a weld.

Comparison of curves characterizing the start of graphitization, moderate and high risk of graphitization of C-Mn steels with data obtained on C-Mo steels show that graphitization in C-Mo steels is delayed but in extreme cases (> 300,000 hours) it can even start at as low temperature as 450 °C - see **Figure 1** [2,3].

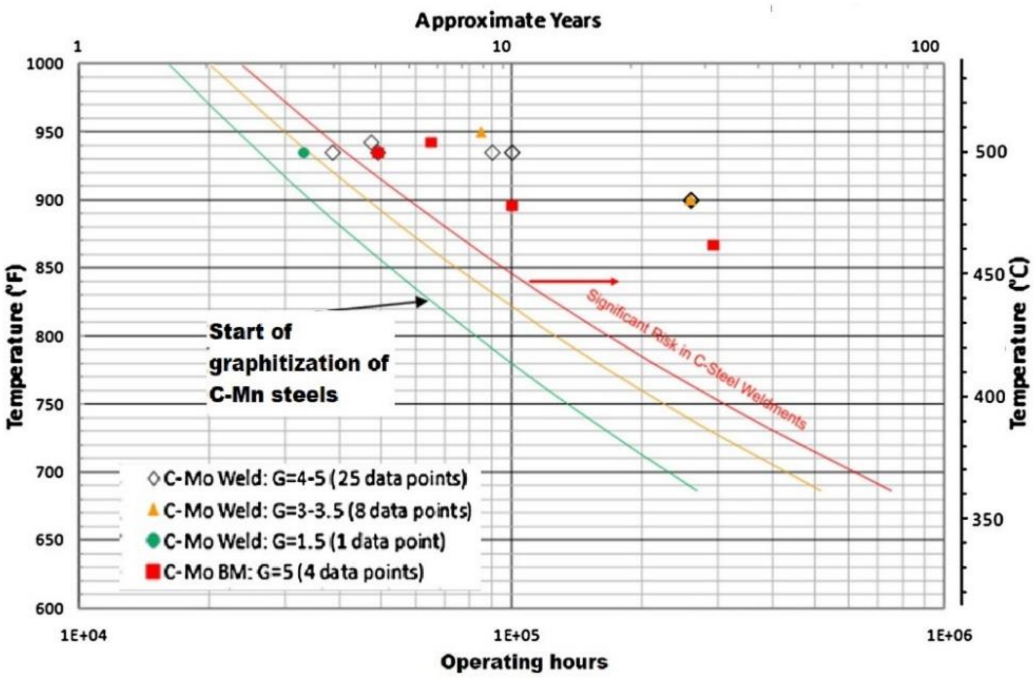

Figure 1 Graphic comparison of the graphitization in C-Mo steel base metal and weldments with the risk curves developed for C-Mn steel weldments [2]

Nevertheless, C-Mn and C-Mo steels are still popular in the pressure system of boilers operating at elevated temperatures thanks to their low cost and easy weldability without preheating and post weld heat treatment. The problem of graphitization of these steels, further gains in importance due to prolonged life of the existing boilers far beyond their design life is actual.

The aim of this paper is to present the results of complex material analysis carried out on a broken bend of a pipeline ø 273 x 20 mm made of 16Mo3 steel after nearly 180,000 hours of exposure at nominal temperature 468 °C. The pipeline connected the outlet header of superheater I and the inlet header of superheater II and the pressure of the steam released during the burst caused the entire steam pipe to bend to the opposite side, broke the hangers and supports and damaged the wall of the boiler room even in the surrounding floors, **Figure 2**.

Figure 2 Damaged part of the pipeline bend

2. EXPERIMENTAL MATERIAL, ANALYSES AND RESULTS

The experimental material was taken close to the burst area and analyses included control analysis of the chemical composition, determination of yield and tensile strength at room temperature and at 450 °C, hardness profile measurement around the pipe circumference and through the pipe wall thickness both in the damaged part and in the unaffected pipe, Charpy-V tests in tangential direction, fractographic analysis of the fracture surface and detailed analysis of microstructure.

Table 1 summarizes the results of control chemical analysis that confirmed the steel grade 16Mo3 and, at the same time, a favorably low Al content under 0.015 %, that should eliminate its negative effect on the heat resistance and graphitization.

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

C	Mn	Si	P	S	Mo	Cr	Ni	V	Cu	Ti	Al	N	As	Sb	Sn
0.16	0.68	0.35	0.013	0.009	0.28	0.07	0.06	<0.003	0.054	0.022	0.014	0.010	0.005	0.003	0.005

The results of the analysis of mechanical properties stated in **Table 2** show a decrease in tensile strength at room temperature below the lower limit stated in the material standard, although all other mechanical properties were in accordance with the requirements. The impact energy at room temperature was also low, when the mean value of three samples was only 1.3 J above the required minimum limit 27 J. The ductile-to-brittle transition temperature (DBTT) was a bit higher than room temperature (+30 °C) and also signal a toughness problem of the material.

Table 2 Mechanical properties of the evaluated pipe bend

Temperature (°C)	+ 20		450		EN 10216-2 (+20 °C)	EN 10216-2 (450 °C)
$R_{p0.2}$ (MPa)	314	329	222	223	min. 270	min. 167
R_m (MPa)	432	432	275	274	450-600	-
Elongation (%)	29.1	27.3	32.7	31.1	min. 22	-
Reduction of Area (%)	70.4	69.5	78.7	79.1	-	-
KV (J)	21, 28, 36		44, 36, 36		min. 27	-

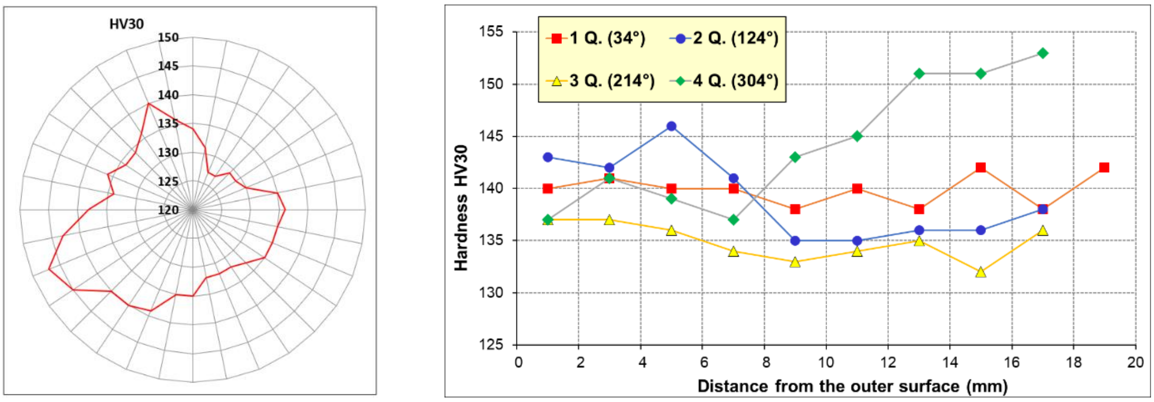

Figure 3 Hardness along the circumference of the steam pipe (left) and across the wall thickness (right)

HV30 hardness was measured around the circumference of the pipe close to the damage, but where the pipe profile was already again circular and therefore not directly affected by the burst. The measurement was made on a cross-section of the pipe, at the center of the pipe wall thickness, and started at a point corresponding to the extrados of the bend. The hardness profile (HV10) across the wall thickness was also measured starting close to the burst line (about 34° clockwise from the extrados with minimum hardness as shown in **Figure 3** left) and then measured in four quadrants clockwise in the direction of water/steam flow. The results of these measurements are shown in **Figure 3**.

The required hardness ranges from 140 to 190 HV and the material is considered satisfactory if the extended limit is 125 to 205 HV. From the results shown in **Figure 3** is clear that hardness lies close to the lower limit due to softening after long-term exposure and the low hardness corresponds well also to the tensile strength.

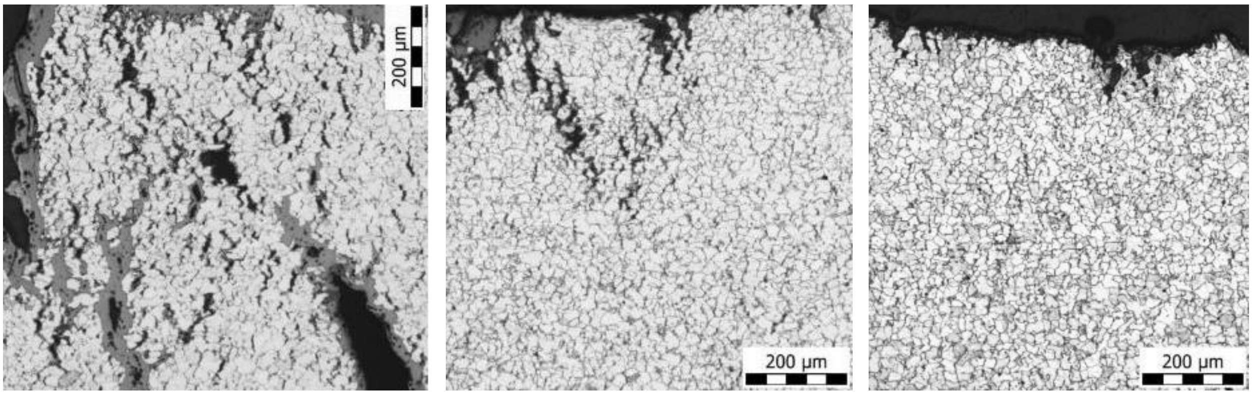

Figure 4 Sample A: Creep cavitation damage at the burst opening (left) 25 (middle) and 50 mm away (right)

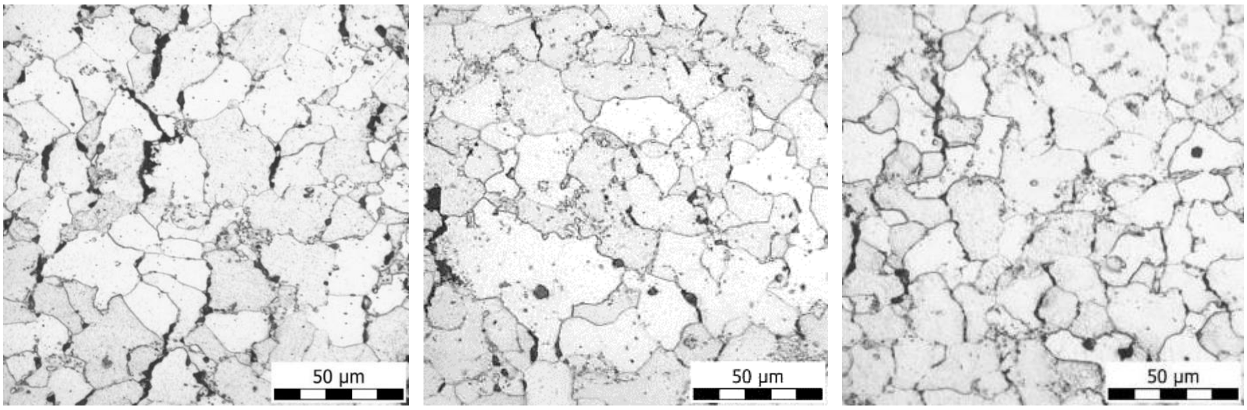

Figure 5 Sample A: Detail of microstructure at the burst opening (left) 25 (middle) and 50 mm away (right)

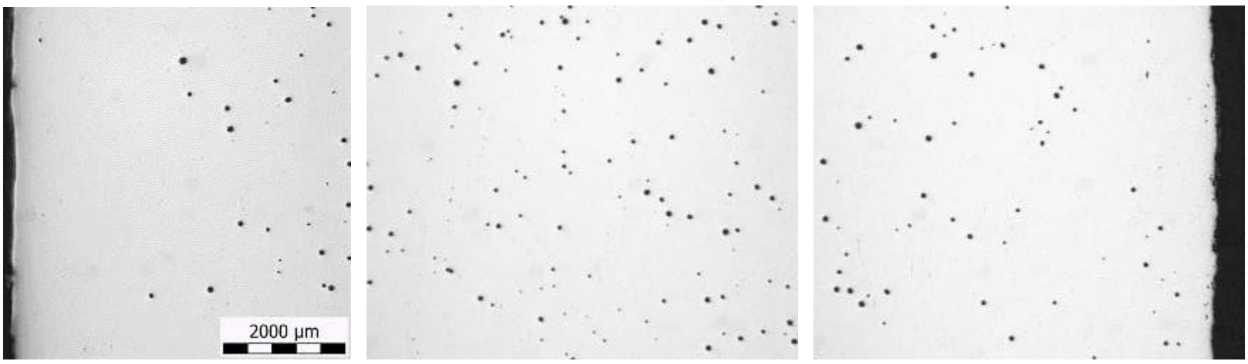

Figure 6 Sample B: Graphite particles in the pipe wall on the extrados of the pipe bend away from fracture

Two metallographic samples were prepared for the analysis of microstructure and damage mechanism: **sample A** from the area of crack initiation and analyzed there and 25 and 50 mm away and **sample B** from the extrados at the end of the damaged bend. Metallographic analysis confirmed the extensive cavitation, namely in the vicinity of the burst opening, with macrocracks and microcracks observed, **Figure 4**, while the damage decreased at greater distance from the fracture**. Figure 5** shows heavily decomposed pearlite and carbides and cavities appearing on grain boundaries. Large particles of graphite, at least an order or magnitude larger than cavities, were observed not only close to the fracture but in all analyzed parts, **Figure 6**.

After cleaning the sample taken for the fractographic analysis just from the expected initiation area of burst by ultrasonic cleaning in the water solution of hexamethytetramine+HCl, the different types of fracture were detected on the outer and the inner side of the pipe wall. Close to the outer surface the fracture mode was mainly intergranular with the appearance of a large number of small voids - cavities, **Figure 7**. On the other hand, close to the inner pipe surface, the combined fracture mode consisting principally of the transgranular ductile fracture with dimples of various size and partly also of the intergranular fracture, **Figure 8**. It is clear that the damage started at the outer surface of the pipe wall and then spread through the pipe wall.

Detailed EDX microanalysis was performed on the Charpy-V notch sample, where numerous graphitic particles were found even at low magnification, **Figure 9**, and the chemical composition of these particles having without exceptions 100 % of carbon content is confirmed in **Figure 10**.

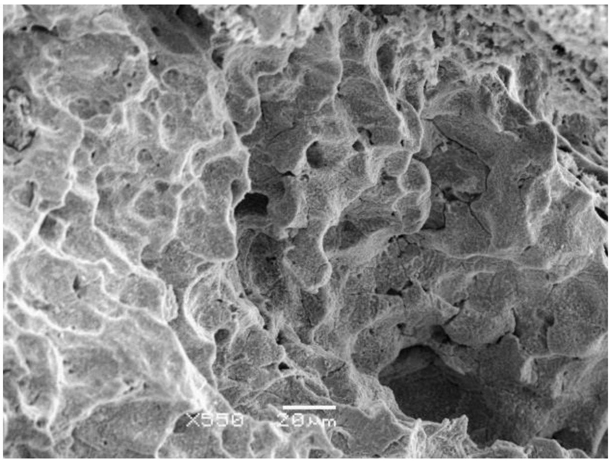

Figure 7 Fracture mode, the outer surface of the pipe

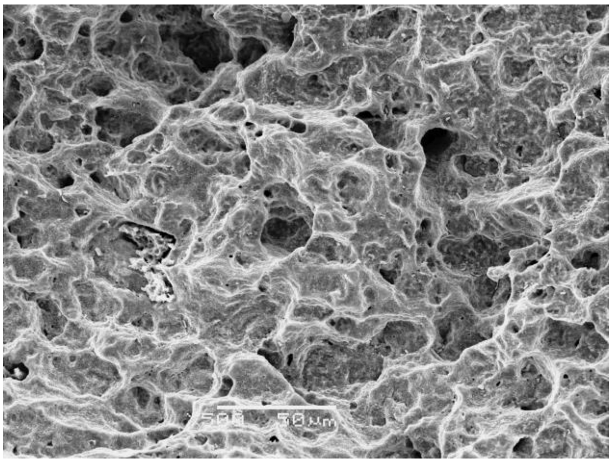

Figure 8 Fracture mode, the inner surface of the pipe

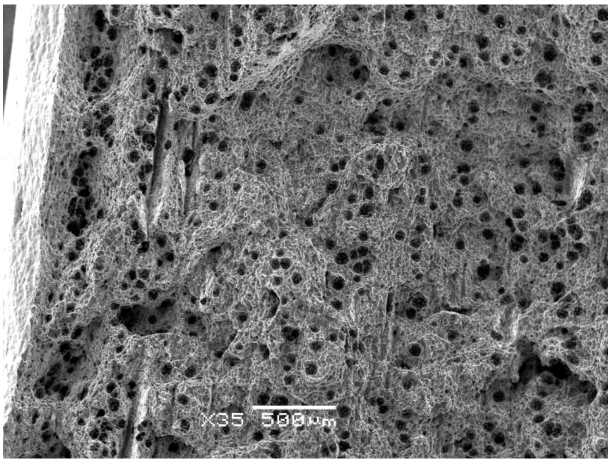

Figure 9 Graphite on the fracture surface of Charpy V-notch sample

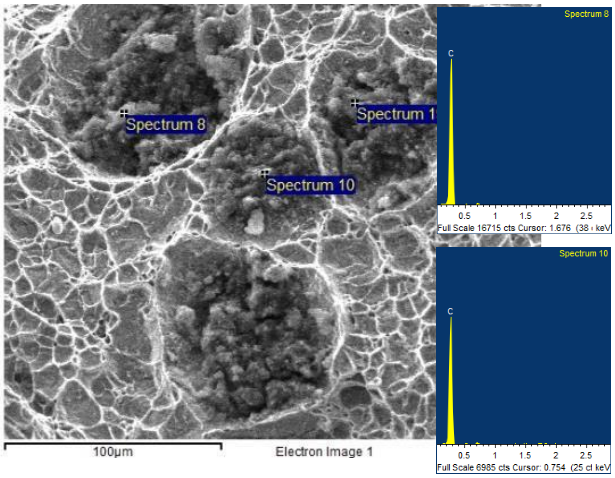

Figure 10 EDX microanalysis of graphitic particles

3. DISCUSSION

After the accident, the calculation of the effective temperature in the damaged bend was carried out based on the operational boiler data that resulted in significantly higher temperature than the design one (506.6 versus 468 °C). It was the consequence of the partial fuel change carried out more than 10 years ago. Of course, this fact significantly affected the real lifetime of the bend. This can be illustrated well even on a very simplified calculation in a straight section of a steam pipe ø 273 x 20 mm, an internal pressure of 9.5 MPa causes a tangential stress 60.5 MPa on the inner surface of the pipe wall, 51 MPa on the outer surface and 55.3 MPa is the mean value in the centre of the wall thickness. In the reported case, it is possible to use the average value of tangential stress σ_t = 55.3 MPa, because for thin-walled pipes (i.e., pipes with a ratio of outer to inner diameter <1.2) a uniformly distributed tangential stress is usually considered calculated by equation (1):

$$\sigma_t = \frac{p \cdot D_{in}}{2 \cdot s} \tag{1}$$

where:

p - the pressure (MPa)

D_{in} - the internal pipe diameter (mm)

s - the wall thickness of the pipe (mm)

The standardized safety coefficient 1.25 for the service life 200,000 hours is used when calculating the maximum permissible stress in the pipe wall, i.e., the stress in this simplified calculation is 69.1 MPa. Times to rupture for both the design and the effective temperatures can be seen in **Figure 11** for the mean creep rupture strength of steel 16Mo3 stated in the material standard. While the predicted time to rupture for the design temperature significantly exceeds a million hours, at 506 °C it is only slightly over 200,000 hours. Despite the considerable simplifications used in this calculation, it is clear that the shift of the operating temperature could significantly reduce the service life of the steam pipe itself.

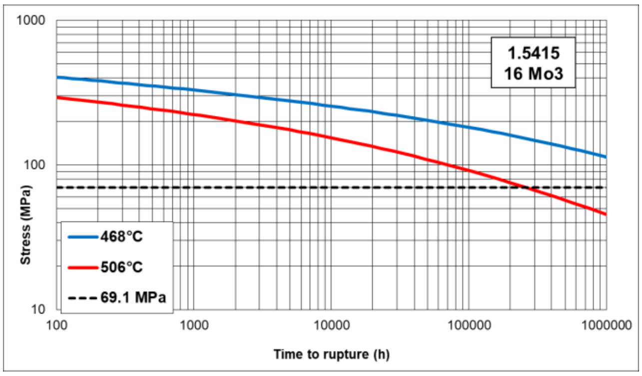

Figure 11 Stress-time to rupture dependence of 16Mo3 steel at various operating temperatures

CONCLUSION

Material analyses performed on samples and test specimens prepared from the burst steam pipe bend showed that the rupture occurred as a result of extensive creep damage in conjunction with the intensive graphitization affecting the entire cross-section of the pipe. The main reason for the creep damage was an increase in the operating temperature in this part of the steam pipe, which was caused by the fuel change. Higher temperature resulted in lower the heat resistance, enhanced decomposition of cementite and formation of graphite particles.

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