CREEP DAMAGE OCCURRENCE IN AN INTER-SUPERHEATER STEAM PIPE AFTER 90,000 HOURS OF OPERATION

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ABSTRACT

After a period of 90,000 operating hours a straight-level segment of the inter-superheater piping has recently experienced axial crack development. The material of the piping is a 14MoV63 steel, with tube dimensions, 609/25 mm. Conditions of 540°C operating temperature, and 180 bar operating pressure, were applied. Investigations have reported that failure was caused by creep. In the effort to identify the causing of actual creep damage development over the straight-level pipe segment, which was initially designed for a 100,000 hour life service, thorough examination of microstructure, fractured surface area and mechanical characteristics of the material have been carried out.

KEYWORDS

Thermal fossil power plant, creep, voids, carbides, inclusion, failure

INTRODUCTION

Fossil power plant (FPP) can often be operated quite economically well beyond the design life. However, exploitation service life of some part of FPP can be shorter than calculated one, in the case of local total material exhaustion. Depending on the dominant failure mechanism in particular case trans- or intercrystall fracture occur.
Creep damage that caused failure in low alloy ferritic steel in FPP component results from /1-4/:

- structure degradation, i.e., thermal softening of matrix and at the same time coarsening of fine dispersed precipitate and associated dislocation interactions
- intergranular creep cavitation

Both processes occur simultaneously but the dominance of either is determined by the initial structural state, purity, conditions of stress and temperature as well as the stress state /1/. When the large number of closely spaced cavities nucleated in grain boundaries, their growth and linkage rate are higher then structure degradation and creep cavitation is the significant damage feature leading to low ductility failure.
When the first process is dominant, the creep rate is determined by increasing the interparticle distance, carbide coarsening, the changes of interaction mechanism between dislocations and particles as well as the particles transition to more stable one.

The aim of this paper was to determine dominating processes during the failure of investigated pipeline component.

BACKGROUND

Failure occurred as a long axial crack on the bottom of the straight part of the 30° bend of the inter-superheated steam pipeline, Fig. 1. Crack propagated through the pipeline wall thickness, in length on the outer side of approximately 410 mm, i.e. 245 mm on the inner side. Pipeline, made of 14MoV63 steel (DIN17175), with dimensions ϕ609x25, had been designed for exploitation life of 100.000 hours under service conditions 540°C and 45 bars, but its exploitation period to the failure was 90.000 hours.

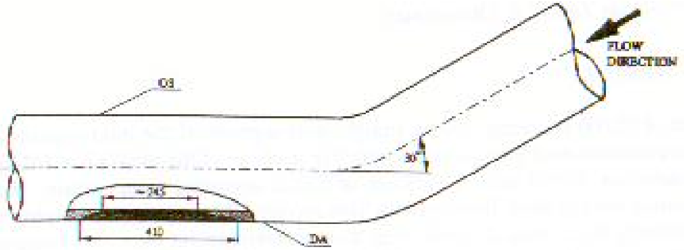


Fig. 1. Schematic view of failure area

Revision of thermal and stress history, visual control, chemical analysis, control of mechanical properties and pipeline wall thickness, metalografical and SEM analyses and X-ray analyses, was applied in purpose of failure determination.

RESULTS

Thermal and stress history. According to the documentation, service parameters (temperature and pressure) did not exceed working limits, i.e. there were not conditions for earlier local failure.

Visual control. Inter-superheated steam pipeline was significantly deformed related to the nominal diameter in damage zone.

Thickness. Thickness, 23.0 to 24.2 mm, was measured on the upper and lower side of cut pipeline part, which was 1300 mm long. Ultrasonic control of the rest of the pipeline detected the wall thickness was in the same range.

Chemical analyses. For spectroscopic chemical analysis specimens were taken from damaged area (DA) as well as from opposite side (OS). Results of chemical analysis of DA and OS, as well as the standard composition and tolerance according to the DIN 17175 are presented in Table 1.

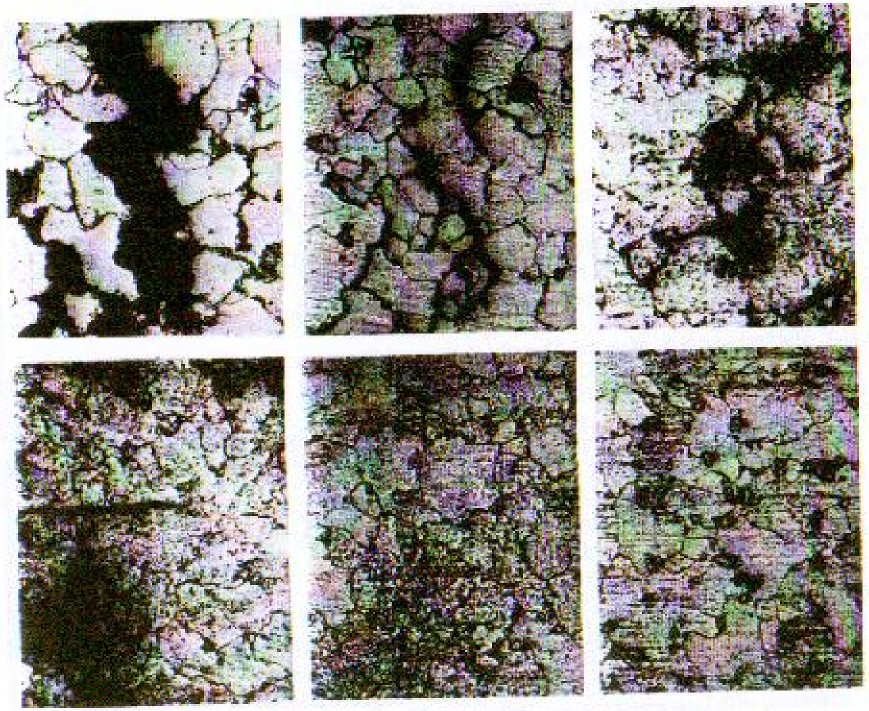
Table 1. Chemical analysis

element	C	Si	Mn	Cr	Mo	Ni	Cu	V	S	P
DA	0.16	0.18	0.39	0.29	0.99	0.15	0.15	0.17	0.032	0.025
OS	0.18	0.32	0.64	0.39	0.54	0.15	0.15	0.23	0.03	0.025
DIN17175	0.1-0.18	0.10-0.35	0.4-0.7	0.3-0.6	0.5-0.7	-	-	0.22-0.32	0.035	0.035
tolerance	±0.02	±0.03	±0.04	±0.05	±0.04	-	-	±0.03	+0.01	+0.01

On the basis of the presented results in Table 1, it can be concluded that local chemical inhomogenity in damaged pipeline material exists.

Mechanical properties. Mechanical properties investigation resulted following values for yield strength and tensile strength of damaged area and opposite side of material, respectively: R_{eh}=295/290 N/mm^2, R_m=464/463 N/mm^2 and R_{eh}=342/345 N/mm^2, R_m=535/536N/mm^2. Obtained results indicate decrease of investigated properties in damaged area. Toughness investigation on standard DVM specimens gave for DA and OS area 43, 49, 46J and 83, 94, 88J, respectively, indicating local ductility decrease in damaged area.

Metallographic analysis. Metallographic specimens, prepared in a common manner, taken from the damaged zone are presented on Figs. 2-7. The basic structure is ferrite, with lot of micro and macro cracks, cavities, extremely large population of different shape carbides, mostly in the grain boundaries, as well as a large number of different size of MnS inclusions, which are propagated through grains and grains boundaries.



Figs. 2-7. Structures of damaged area (500x)

Scanning electron microscopy and EDAX. Fig. 8 shows the fracture features of toughness specimen, taken very nearby the crack. The fracture is ductile, some of the cavities are visible, as well as the inclusion, which is by EDAX analysis of silicate type, Fig. 9. Structure features, obtained by SEM analysis of specimens from damaged area, which are deep etched, are presented in Figs. 10-16.

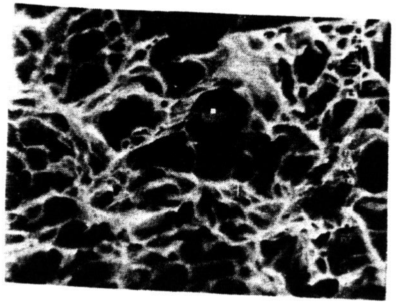


Fig. 8. Fracture features of toughness specimen

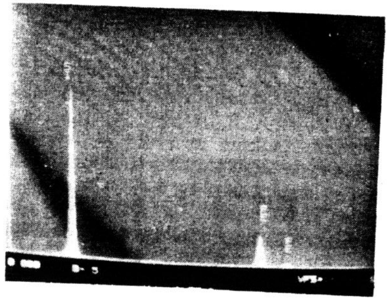


Fig. 9. EDAX of inclusion, silicate type

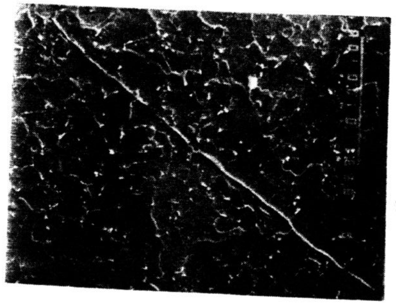


Fig. 10. Elongated MnS inclusion with cavities, many alloyed, different shape, carbides

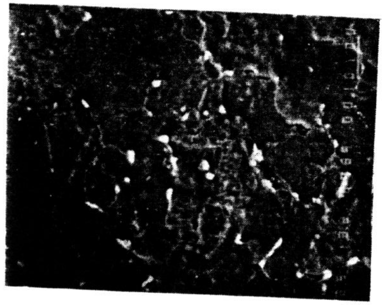


Fig. 11. Secondary microcracks, cavities, alloyed carbides

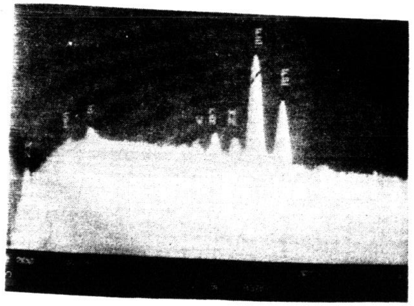


Fig. 12. EDAX from Fig. 11. Alloyed carbide with segregated MnS on its boundaries

Fig. 13. Alloyed sulfide (MnCr)S, with micro cracks, cavities, carbides

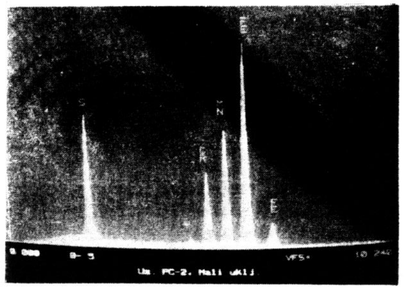


Fig. 14. EDAX from Fig. 13

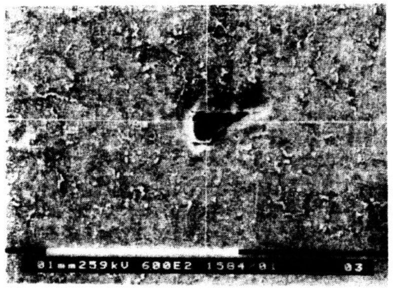


Fig. 15. Silicate inclusion, carbide, cavities, micro cracks

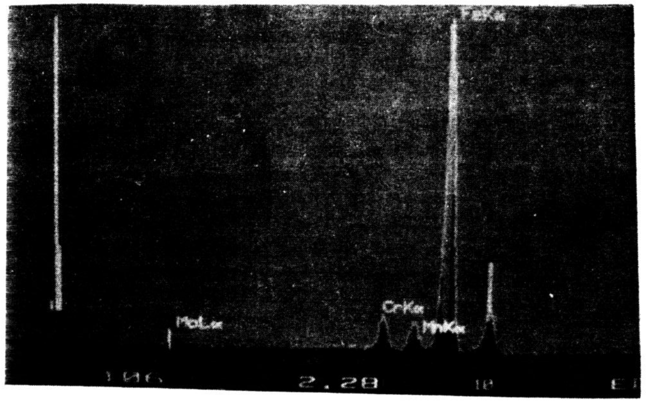


Fig. 16. EDAX of alloyed carbide particles from Fig. 11

On the basis of SEM and EDAX analysis, presence of many large alloyed carbides of $(MoCrMnFe)_3C$, $(MoFe)_{23}C_6$, $(VCr)_xC_y$ and Mo_2C types in grain boundaries, plenty of elongated MnS inclusions through grains and on grain boundaries with cavities, polygonal alloyed sulfide (MnCr)S, silicate inclusions, Al_2O_3 inclusion, as well as secondary cracks caused by carbides and cavities, are noticed.

DISCUSSION

In order to interpret the results, it is useful to consider the difference between reaction which determined properties of material and the mechanism which leads to material exhaustion before, or during, the calculated lifetime of component.

Creep strength of 1/2Cr1/2Mo1/4V steel is determined by beneficial properties due to precipitation hardening of solid solution and dispersion hardening due to interaction of dislocations and small, well distributed carbide particles. Alloying elements, Cr, Mo and V, in this steel must be present in well determined amount and with mutual ratio of 1/2:1/2:1/4, respectively, because each element has a proper influence. Only in the case of certain ratio in steels, those elements have optimal effect on properties and behaviour of material at increased parameters (temperature and pressure).

Creep mechanism, for Cr-Mo-V steel, basically may be due to:

- structural degradation with loosing of precipitation and dispersion strengthening and significant changes in carbide distribution and carbide transformation from common cementite type (Fe_3C) to transformation carbide (alloyed M_3C-$M_{23}C_6$-Mo_2C) and finally, but less possible to stable M_7C_3 and M_6C carbides;
- intergranular creep cavitation.

Usually, according to the literature /3-5/, creep cavitation was mostly the reason for damage on FPP components. It means, that resulting mechanism for damage is a cavity nucleation and their growth in grain boundaries which are distributed perpendicular to direction of acting tensile stress.

But, according to the obtained results, the dominant fracture mechanism of investigated pipeline component was strong local structural degradation.

On the basis of presented chemical analysis, the local chemical inhomogenity is noticed with significant differences of mutual ratio of Cr, Mo and V (1/4:1:1/3 to 1/2:1/2:1/4).
The alloyed elements ratio have influence on their different distribution in some structural components (solid solution, dispersion and carbide types), during the final heat treatment before FPP building. It means, that local structural changes, under pipeline service conditions, hadn't occur according to the rules.

Optical, SEM and X-ray analysis present enormous population of large size carbides, separated on the grain boundaries. Carbide particles are different in shape from elongated (which are a film like in grain boundaries) to polygonal, lens-like and spheroid. It is very interesting to note that the carbide particles are mostly located on the grain boundaries in direction of acting stress (compressed boundary). EDAX and X-ray analyse show presence of $(FeCrMoMn)_xC_y$ *(as in /6/)* and $(VCr)_xC_y$ alloyed carbide types, with different but somewhere with high amount of Mo, $M_{23}C_6$ (with Fe and Mo) as well as Mo_2C carbide. It is known /1/, that during the type and dispersion changes of carbide phase, from metastable cementite, through transition carbides, to stable ones, strength properties are decreasing.

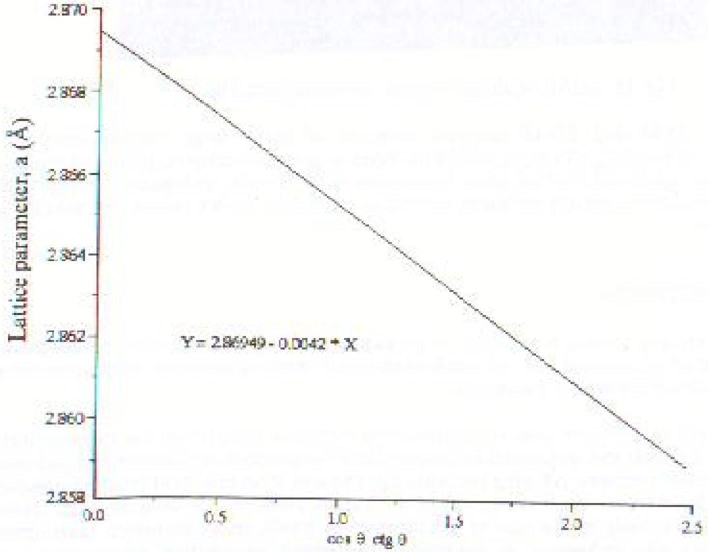


Fig. 17. Determination of true lattice parameter

Determination of crystal lattice parameter of solid solution, indicate unalloyed solid solution, as shown on Fig. 18, which means that measured lattice parameter is very close to the lattice parameter of the pure ferrite. Consequence of that is the decreasing strength characteristic at raised temperatures.

On the basis of the obtained results it is clear that the main cause of structure degradation is unbeneficial distribution of molybdenum and vanadium as a principal alloying solid solution atoms. Basic role of Mo, i.e., strengthening of solid solution due to solving and stabilization of fine dispersed VC precipitate, is acquired when there is 0.4-0.6% in steels. Condition for that is there should be enough other carbide forming elements (Cr is inadequate in this case) and that Mo, as well as V, in minimal degree during exploitation, are transiting into the carbide phase /4-5/. In contrary, obtained results are showing that Mo, as well as V, are significantly present in carbide phase, i.e., in negligible amount in solid solution.

Because of enormous separation of large carbides on the grain boundaries, which impeded dislocation movement, and boundary accommodations by sliding, high stress concentration was created on boundaries, resulting in premature pipeline failure.

Some of many inclusions, whose presence was detected by SEM and EDAX analysis (MnS, MnCrS, Al_2O_3, silicates), act as cavity nucleation sites, but obviously their nucleation and growth rate was less than structural degradation rate of material.

CONCLUSIONS

On the basis of the results and its analysis, it can be concluded:

- failure of investigated pipeline component was consequence of creep by means of structural degradation;
- structural degradation was caused by local chemical inhomogenity resulting from unproper manufacturing;
- lack of chromium and excess of molybdenum influenced on irregular redistribution of these elements between particular structural components;
- during exploitation creep strength of material decreased because of loss of beneficial precipitation and dispersion strengthening effects;

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