Life Assessment of Creep Exposed Components, New Challenges for Condition Monitoring of 9Cr Steels

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1 Introduction

Steam pressure loaded, high temperature components in power plants have a high damage potential. Although safe design and careful condition monitoring have always been of great concern for the high temperature industry, today this issue is even more important with the higher and higher steam parameters of low emission power plants. Standards, rules and guidelines exist worldwide to avoid catastrophic failures and to deliver the right basis for condition based inspection.

Of course, technical advances in computer application for design, condition monitoring, instrumentation and high temperature materials are driving forces for the enhancement of life prediction and assessment procedures. In addition, understanding of material degradation is essential for improved inspection and maintenance scheduling without taking the risk of decreasing reliability, availability and profitability of the plant.

Today, metallographic replica testing is the most common inspection method for creep damage monitoring in piping systems and steam boilers. As ductile materials, like 9Cr steels (parent material), tend to form cavities less than other materials, creep damage propagation needs to be characterised by additional accompanying methods. In this context the authors report on recent findings on the material degradation of 9Cr steels, and the conclusions for condition monitoring.

2 Technical Rules and Regulations for Design and Condition Monitoring

2.1 Component Design

Power plant components are classified, according to the material operating temperature, into those which are creep exposed, and others which are operated below the creep range. Design codes define characteristic temperatures, which vary somewhat between the codes because of the different procedures employed, below which creep is not considered for particular classes of material (Figure 1).
In Germany, the design of creep exposed components follows the rules of the TRD300 /2/ series. Furthermore, other codes such as ASME are used depending on customer’s requirements. In general, these design codes produce varying wall thickness, component life and other parameters depending on the specific code which was used and its inherent conservatism.

As the creep rupture strength of the actual component material is in practice unknown, safety factors are introduced, e.g. $1/0.8 = 1.25$ (see Figure 1), which result in more conservative design.

### 2.2 In-Service Inspections

Deviations in actual component life, even between components of the same geometry and loading, result in different life consumptions and different residual life after the same operating hours. This fact needs to be taken into account for in-service inspection and maintenance.

According to German TRD 508 /3/ and VGB guideline VGB-R 509L /1/ in-service inspections are required to start at the earliest of the following:

- Total life consumption from creep and fatigue of $e = 60\%$ (or $e_w = 50\%$ for fatigue only)
- After about 70 000 operating hours (OH) for material 14MoV6-3 and after about 100 000 OH for other heat resistant steels.
Replica tests, which allow the classification of material degradation (Table 1), and other NDE tests are conducted for material characterisation during in-service inspections.

### Table 1. Evaluation of material degradation of creep exposed components according to VGB-TW 507 /4/

<table>
<thead>
<tr>
<th>Assessment class</th>
<th>Structural and damage features</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>As received virgin material</td>
</tr>
<tr>
<td>1</td>
<td>Creep exposed material without cavities</td>
</tr>
<tr>
<td>2a</td>
<td>Advanced creep exposure, isolated cavities</td>
</tr>
<tr>
<td>2b</td>
<td>More advanced creep exposure, numerous cavities without preferred orientation</td>
</tr>
<tr>
<td>3a</td>
<td>Creep damage, numerous orientated cavities</td>
</tr>
<tr>
<td>3b</td>
<td>Advanced creep damage, strings of cavities and/or grain boundary separations</td>
</tr>
<tr>
<td>4</td>
<td>Advanced creep damage, microcracks</td>
</tr>
<tr>
<td>5</td>
<td>Large creep damage, macrocracks</td>
</tr>
</tbody>
</table>

In addition, the as built geometry has to be measured, unless this is available from initial start-up data. After a theoretical life consumption of 100 %, all components have to be inspected at least once. After this only testing of the highest stressed components is continued. Component replacement is required for the following findings:

- Orientated creep cavities were discovered on a large scale.
- Viscoplastic strains reached 2 % (or 1 %, but a creep strain measuring point was installed before reaching a total life consumption of $e = 60 \%$).
- Critical cracking, due to creep and fatigue, was found.

### 3 Stress Analysis

#### 3.1 Strength Hypotheses

In general, the mechanical characteristics of the material are obtained from uniaxial tests (stress test, creep test etc.), which do not agree with two (2D-) or, more often, three dimensional (3D-) stress fields in real components. Even uniaxial loads result in
3D stress fields at geometrical inhomogenities such as grooves, notches and drill holes. Thus, reference stresses were introduced to correlate behaviour at geometric features with that measured on uniaxial specimens. Their use depends on general material and material cracking behaviour. The energy theory of distortion (according to Huber, v. Mises, Hencky) provides a reference stress

\[
\sigma_{\text{eqv, M}} = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right]}. 
\]

The energy theory of distortion is used for ductile material behaviour in particular, and, due to their viscoplastic deformations, it is also used for creep exposed components.

Creep damage is considerably affected by the “multiaxiality” of the stresses. Multiaxiality parameters, such as the following, were introduced to allow the characterisation of this effect:

\[
\text{TF} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_{\text{eqv, M}}} /5/ 
\]

\[
h = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_{\text{eqv, M}}} /6/.
\]

### 3.2 Multiaxiality of Notches

Higher multiaxiality of stress field means that the material deformation is restricted. The material response under these conditions is studied in creep tests on notched specimens. Redistribution of stresses, with resulting stress relief at the notch root, is the principle response of ductile materials. Hence, notched specimen fails later than smooth specimens at the same nominal load. When notched specimens fail before smooth uniaxial specimens, creep embrittlement of the material is the explanation.

### 3.3 Stresses in Welds

Creep properties of welds, i.e. minimum creep strain rate, creep rupture strength and creep ductility, are generally different from those of the parent material. In addition, welds represent a non-homogeneous structure consisting of parent metal, three characteristic zones of the HAZ (coarse grained zone, fine grained zone, intercritical zone, see Figure 2) and weld metal. The micrograph of the outer, i.e. intercritical
zone shows martensitic and high tempered zones in parallel due to lower peak temperature during welding. The limited carbide dissolution affects low alloyed martensite /7/. The different creep deformation characteristic of these individual zones results in constraint of transverse deformation during long term service. Hence, a multiaxial stress state exists, as with notches, which may become even more complex due to mismatching in the welds. The intercritical zone is the weakest region of the weld and represents the service life limiting zone of the component with so called type-IV-cracking developing, sometimes early in service life.

Figure 2. Schematic cross section of a weld showing typical microstructural zones /8/
3.4 Conversion of Findings from Specimen Tests to Real Components

In general, conversion of test results, from uniaxial creep specimens to real components, gives conservative predictions of service life and life consumption for the following reasons:

- Multiaxiality of stress field, which has already been discussed in section 3.2.
- The creep test runs under constant load for the whole test duration. Hence, the actual stress in the specimen cross section is increasing up to the end of the test, due to necking of the specimen, which results in a shorter fracture life. This is a special effect of specimens which is not found in components.

4 Recent Findings on Material Degradation of 9Cr Steels

Various attempts and procedures exist to correlate the life consumption of components with the microstructure through the distribution, density and orientation of cavities. These correspond, more or less, with reality for the following reasons:

- Microstructural changes in cavity formation show some differences between the various heat resistant steels. Differences were even found between various batches of the same material.
- Design rules, e.g. TRD508, define theoretical end of life by the lower limit of the scatter band of creep rupture strength, i.e. they assume the material performance of the as built component is equivalent with the weakest material in the scatter band. In most cases the real creep strength is higher, but, unfortunately, unknown. Thus, the material and/or the specific component incorporates a large reserve of creep life. Of course, creep tests can be conducted to investigate the creep strength. However, these tests are expensive and time consuming especially as sufficient representative results are required for a good extrapolation. Only sophisticated calculations, using material data from the specific heat, from NDE and/or information available from certificates of the as received steel condition, are able to reveal these reserves, and to overcome the sometimes considerable conservatism. Z-Factor-Method /9, 10/ is one of the possible procedures.
- Material degradation in components deviates from that in specimens as the stress field and multiaxiality are different.

The effect of multiaxiality on creep damage was investigated for three heat resistant piping materials (14MoV6-3, 10CrMo9-10, X10CrMoVNb9-1) in the German AVIF funded research project /11/, which represents the first systematic investigation of this subject. Pressure tests were conducted on smooth and notched hollow cylinders.
(Figure 3). Multiaxiality was controlled by using external axial tensile and pressure forces of various levels.

Figure 3.
Smooth and notched hollow cylinders for laboratory component tests /11/

Material degradation was inspected by conducting replica tests at the outer surface and the notch root. These tests showed significant differences in the material’s response:

14MoV6-3:
This material tends to develop creep cavitation strongly. Significant dependence of creep damage on true creep strain $\varphi$ and multiaxiality parameter $h$ was found (Fig. 4).

Figure 4. Effect of multiaxiality and creep strain on microstructure of 14MoV6-3 steel /11/
The higher the multiaxiality parameter $h$, the higher the damage evaluation class and density of cavities at the same creep strain. The graph shows, that a maximum creep strain of 2%, according to /1/, means a damage evaluation class 2a (isolated cavities) for the uniaxial specimen with $h = 0.33$. In contrast, orientated cavities had already been found in the pressurised pipe with $h = 0.58$ at the same creep strain.

**10CrMo9-10:**

This material is less sensitive to cavitation even at high multiaxiality.

**X10CrMoVNb9-1 (P91):**

The investigation of 9Cr material showed very different behaviour of the specimens with regard to cavities. Batches with higher ductility were less sensitive to cavity formation than batches of lower ductility. Using results from creep tests no correlation was found between the density of cavities (quantity per mm$^2$), axial strain and applied stress (Figure 5, /11/).

**Figure 5.** Density of cavities in various batches of X10CrMoVNb9-1 vs. stress and axial strain /11/.
Component tests of ex-service pipe bends confirmed these results from the specimen tests.

A further project funded by VGB /12/ addressed changes in microstructure during creep of 9Cr steels in particular. For this purpose creep specimens from interrupted tests were broken open for metallographic investigation, which gave the following results:

- Definite correlation was discovered between creep damage propagation and the decrease of creep ductility.
- The degree to which creep ductility reduces, depends on temperature and the specific batch of material.
- Cavities were typically found at former austenite grain boundaries and martensitic laths.
- Creep damage propagation, detectable by optical microscopy, was found at the beginning of tertiary creep \( t/t_{\text{fracture}} = 0.5 \), whereas creep strains were higher than in low alloy steels. The beginning of tertiary creep represented by time \( t_{2/3} \) and creep strain \( \varepsilon_{2/3} \) is presented in Figure 6. However, these results were gained from uniaxial tests. The response of the material to multiaxial stress state was not investigated and is expected to be somewhat different.

In summary, at present the available results from material tests of X10CrMoVNb9-1 (P/T91) and X11CrMoWVNb9-1-1 (E911) demonstrate that essential gaps in understanding of creep damage propagation exist, which still remain to be closed. This awareness was the background for the further research project /13/, which is intended to deepen the existing findings and to generalise them by investigation of E911 material. This project addresses particular criteria for life assessment, on the basis of creep damage propagation.

For this purpose the following tests have been conducted:

- Creep tests of P91 and E911, which deliver creep curves for both materials.
- Feature tests of smooth and notched hollow cylinders, under internal pressure and axial loading, to simulate different levels of multiaxiality.
- On-site measurements: main steam line of the 800MW unit “B” of the supercritical lignite fired power plant “Schwarze Pumpe” was instrumented with various probes, amongst them capacitive strain gauges, which allow the online measurement of creep deformation. Additional material investigations such as Ultrasonic (US-) laminography, geometrical measurements, hardness tests and replica tests are going to be conducted during main inspections.

Numerical analyses complete the experimental programme.
Figure 6. Beginning of tertiary creep for P/T91 and X20CrMoV12-1 /12/
5 Conclusions for Condition Monitoring and for Technical Rules

Metallography based on on-site replica tests represents a well accepted method for the condition monitoring of creep exposed components. However, plant and research experience show that cavity formation is less distinct in ductile materials, such as in 9Cr steels, where this process starts very late. For this purpose other methods of condition monitoring need to be found. Features of replica testing are the small inspection area and the limitation of analysis to the outer surface only, without information on damage within the wall. These aspects restrict the use of replica tests. In addition, distinct inhomogeneous stress states and local different microstructures require metallographic investigations in various positions within the component for statistical reasons with resulting increase in costs.

US-laminography /14/ represents an advanced test method for damage detection, which allows to inspect larger areas. The component is subjected to US Rayleigh surface waves of various wave lengths. Sound velocity is scanned starting from the surface at different depths. The change in sound velocity along the wall is used as a damage criterion, as damaged regions are known differ from virgin ones in sound velocity. This method has already been proved on components of various materials.

Creep deformation or creep strain measurements by capacitive gauges represent another method. Today, measuring techniques are also reliable enough for in service measurements, and results are of high resolution. However, high costs and very local measurement are considerable disadvantages. The Creep Replica Method /15/ is a lower-priced alternative. For this two measuring marks are applied on the component surface and their separation is measured repeatedly by replica test and subsequent SEM evaluation. Accuracy is reported to be in the range ± 0.2 %. Finally, the triangulation method /16/ can be applied. However, this optical measurement is of less accuracy than, for example, capacitive measurement.

However, traditional creep expansion measurement using special “warts” or “pips” at the outer surface, for measurement of diameter or circumference, is the most cost-effective method. Of course, its use is restricted to components like pipes and headers.

6 Summary

In principle, the concepts of condition monitoring of creep exposed power plant components, which have been developed for about 20 years, have proved
themselves. However, 9Cr steels, which have been used in power plants since the early 90’s, are of higher ductility than most of the traditional high temperature materials. Hence, creep damage propagation is different. Modified condition monitoring strategy is necessary.

Thus, extensive efforts are being undertaken to investigate these materials and material degradation in particular considering the effect of cast-to-cast variation.

The classical replica test will remain one method of creep damage monitoring in the future. However, it needs to be accompanied by other qualified methods for ductile materials like 9Cr steels. Of course, costs need to be considered as well.

The question, if existing values of allowable creep strains need to be revised remains open.

References


/12/ Bendick, W.; Hahn, B.; Schendler, W.: Development of Creep Damage in Steel Grades X10CrMoVNb9-1 (P/T91) and X20CrMoV12-1 – Results from the VGB-research Project 160. VGB PowerTech 12/2001, pp. 98-101


