ONGOING PRACTICAL ACTIVITIES WITH REGARD TO CREEP

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This paper describes activities with regard to creep and remanent life expectancies of components operating at high temperatures. Research and regulating work are discussed based on failure analyses and operational practice.

1 INTRODUCTION

In the Netherlands components employed under creep conditions are subject to design criteria which define an allowable stress for a specified design temperature. This stress is obtained from standard creep rupture data (DIN, ISO) by applying a safety factor to the mean stress of 1.5 (or a safety factor to the minimum stress of 1.2) to cause rupture after a specified time, normally of the order 100,000 h. The safety factor is incorporated to accommodate material property variability and operational fluctuations. Uncertainties often exist in these areas and consequently doubt exists regarding the true life expectancy of components.

The electricity supply companies need to assess the remaining life of components which have operated for extensive periods at high temperatures and of components approaching their design lives. These requirements arise from three main considerations:

- to prevent high temperature failures and thus to avoid costly unscheduled outages.
- to predict when component replacement is necessary and thus allow extension of life.

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- to meet safety reflections as formulated by the Dutch Government Authority "Dienst voor het Stoomwezen".

2 COMPONENTS AND MATERIALS

In developing a methodology for remanent creep life determination, in first instance consideration should be given to the types of components and materials most likely to require such determination. Simple criteria can be used to determine application areas which could most benefit from developing accurate life prediction capability. In general these are:

- plant design, operational practice, failure statistics, difficulties and uncertainties of repair, cost of associated outages and identification of failure cause.
- An electricity supply plant availability study performed in 1981 by the Working Group Remanent Life of the Dutch Welding Institute "Nederland Instituut voor Lasttechniek" indicate, for example, for the period 1967 through 1981 a high frequency of failure in boiler tubes, see figure 1. From the 139 failures investigated, approximately 75% referred to boiler tubing.

Running through the failure analysis reports a classification of failure causes was made into errors introduced during design, material manufacture (e.g. wrong heat treatment), erection (e.g. wrong welding procedure) and operation.

An accurate means of life assessment seems to be a priory unlikely in view of the wide variation in operating conditions and thus in life controlling mechanisms, for tubing in different locations within the boiler. Therefore, it is often preferred to treat this problem for an individual boiler by means of an analysis of the tube failures themselves. Besides, boiler tubing can be replaced relatively easily and the outage time for an individual failure is low, with correspondingly modest costs.

In contrast, assessing the life expectancy of large components such as steam headers and steam pipes is extremely wanted. They are very expensive and difficult to replace. Replacements must be ordered timely before the eventual failure event.

Traditionally, the materials used in older fossil fired plants up to temperatures of approx. 570°C have been the low-alloy ferritic steels 1Cr1Mo (13CrMo4.4), 2Cr1Mo (10CrMo9.10) and 9CrMoV (14MoV6.3).

An accurate means of life assessment is therefore urgently needed for these materials, more urgent than for austenitic steels and higher alloyed ferritics (12Cr, X20CrMoV12.1) which have been increasingly applied in recent years.

The first example refers to a 21CrMoe steam header with crack-like indications detected by magnetic particle testing in the welds between the outlet nozzles and the header, on the outside of the header. The component had been approximately 85,000 h in service at a temperature of 530°C. Although calculations showed that the header did not yet suffer from significant creep damage, the header was replaced and afterwards investigated in the KEMA metallurgical laboratory.

It became clear that the cracks, several mm deep, were oriented in longitudinal direction of the header on each side of the nozzles and were located in the weld material itself and to a much lesser extent in the coarsely grained heat-affected zone, not in the finely grained heat-affected zones from the base materials. This fact and the observation that internal oxidation near the cracks had taken place, led to the conclusion that the cracks had been formed by solidification cracking during welding and possibly some minor cracks by reheat cracking during stress relief heat treatment.

In other words, the cracks were present the first day of operation and grinding out these cracks after 85,000 h of operation would have saved the header.

Normally, creep damage near welds is located between the finely grained heat-affected zone and the unaffected base material, see figure 2. This is demonstrated by a single crack detected in a 14CrMoV steam pipe system after 98,000 h of operation at a temperature of approximately 540°C. The crack was located on the outside of a pipe adjacent to a weld to one leg of a forged Y-piece. A sample of material was removed and studied in the laboratory. This was about 0.1 in. deep and oriented in the region between the finely grained heat affected zone and the unaffected base material as shown on figure 3, and is regarded as typical of a macro creep crack: partially distributed single creep voids (less clear due to etching of the metallurgical structure) and micro cracking formed by coalescence of voids step by step.

The fact that the crack was located only in one pipe leg and only covered a small percentage of the circumference of the pipe, did presume that external bending loads contributed to the developing of the creep crack. Additional stresses could have been caused by the fact that the crack was located in a wall thickness transition region from pipe to (thicker) Y-piece leg. Finally, the creep strength from the heat-affected zone might have been lower than from the original unaffected base material. The expansion behaviour of the pipe system was verified, corrected and the pit caused by the sample removal was (temperally?) repaired by welding.

3 SOME FAILURE EXAMPLES

A short description of some failure examples from Dutch power plants may illustrate difficulties and uncertainties encountered during remanent life investigations.

*Remanent life calculations based on internal pressure and creep rupture data from 9CrMoV base material demonstrated no significant creep damage had occurred.
A third and last example refers to creep cams welded on a straight 12Cr steam pipe during manufacture of the pipe system. These cams were intended as help for measuring periodically a possible increase in the creep strain during operation of the pipe. No increase in strain was observed after 60,000 h of operation at a temperature of approximately 540°C.

Inspection by magnetic particle testing, however, revealed indications on the pipe directly adjacent to the welds. A metallurgical analysis of a removed sample showed that the indications were caused by a preferential corrosive attack, approximately 0.2 mm deep, of the ferritic pipe material, also found in tubular dissimilar austenitic/ferritic welded joints. And indeed, the weld was found to have an austenitic metallurgical structure. The cams and the austenitic material were removed and the corrosive attack was ground out smoothly.

5. PRACTICAL RESEARCH

The practical research activities are based on experience with failure analyses and on general problems encountered during remanent life determinations. The work is partly performed in own house and partly contracted out to the Electrical Research Association Technology Ltd. (ERA, Leatherhead, UK) and the Dutch Welding Institute.

5.1 KEMA PROGRAMME

The KEMA programme consists of work on:
- verification of the merits of uniaxial short-duration creep rupture tests at elevated temperatures.
- the effect of test-piece oxidation during uniaxial creep rupture testing at elevated temperatures.
- creep rupture behaviour of welded 1Cr5Mo (Ø 72x6 mm) pipe under internal pressure and external bending load, and uniaxial creep rupture testing of test-pieces simulating the various heat-affected zones in welded 1CrMoV.
- creep rupture testing of welded Esshete 1250/310 (Ø 33x9 mm) pipe under internal pressure and external bending load, and uniaxial creep rupture testing of the coextruded material.
- quantitative assessment of structural metallurgical parameters for predicting the remanent life.

Uniaxial short-duration creep rupture tests refer to tests at elevated temperatures under constant load conditions, initially at the nominal service or hoop stress (iso-stress tests).

At least five elevated temperature rupture data are used, for a fast test result in the range of 100 to 1,000 h.

Then linear extrapolation in the coordinate system log \( t \) over \( 1/T \) or log \( t \) over \( T \) gives the time-to-rupture \( t \) (remanent life) at the service temperature \( T_s \). The
method has been proposed as a preferred route to stress extrapolation by many workers*).

The programme for experimental verification of this method is shown schematically on figure 6. The main programme part B consists of loading 1CrMo, 2Cr1Mo and 2Cr1MoMo tubes under internal pressure and higher temperatures. Periodically material will be removed from the tubes and tested uniaxially at elevated temperatures to determine the remanent life AFD. At the end, the final rupture event of the last remaining tube section should have been predicted by the uniaxial elevated temperature test method.

Because the design of high-temperature equipment is still based on the use of uniaxial creep data it is repeated to a large extent on uniaxially loaded strips. The outcome of this programme A can be of use for quality assurance work during erection of a plant.

Programmes for some of the same materials as used in the other programmes, however in unstrained conditions. This probably makes it possible to discriminate between temperature and stress-induced changes in the metallurgical structure. Finally, to study the merits of the short-duration elevated temperature test method in combination with the life-fraction-rule

\[
T_1 + T_2 + T_3 + \ldots = 1 \text{ for rupture, two tubes}
\]

2Cr1Mo are loaded in programme D under constant internal pressure and under varying temperature conditions, such as during actual operation does occur. The tubes are expected to rupture at a certain time due to a certain temperature giving a time-to-rupture t_p. The length of time this paper was written, the first material test-pieces in programmes A through D were removed after 12,500 h of accumulated service.

Oxidation during creep and rupture testing of low-alloy steels in air can significantly reduce the time-to-rupture. The effect is demonstrated in figure 7, which shows a comparison between isostress tests in air and nitrogen with 5% of hydrogen on 0.3 mm test-pieces removed from the steam header described in chapter 3. By testing in air, the life expectancy of the header is reduced by a factor of 2. Of course, this is of great importance since design and remanent life appreciation are based on tests in air. Any unnecessary (over)conservatism should be avoided.

In trying to simulate failures in welded 1CrMoV, as shown on figure 3, welded tubes 0.72x6 mm are loaded in a set-up under an internal pressure of 70 bar at temperatures 550, 570 and 590°C and with an external dead weight.

causing an axial bending stress of 105 MPa, see figure 8. Then the intention is to repair the tubes by removing cracks that have formed, followed by welding and retesting in the set-up.

There are reasons to believe that the various heat-affected zones in welded 1CrMoV do have creep properties inferior to those of the unaffected base material. This is why test-pieces will be loaded uniaxially under constant load at elevated temperatures after the heat-affected zones have been simulated in the test-pieces in a weld simulator. The plan is under consideration to test also the various heat affected zones from a weld which has been in operation for 80,000 h.

Since 1969 coextruded Esshet 1250/310, developed by T.I. Chesterfield, has been used and studied in coal-fired units in the UK. The material consists of 3.5 austenitic AISI 310 on the outside for protection against corrosive attack, the inside is made from an austenitic 15Cr10Ni, 6 Mn material with additions of Mo, Nb and V. The coextruded material should be able to withstand temperatures up to and even beyond 700°C.

For possible use in Dutch boilers isostress tests at elevated temperatures are performed and the welded material will be tested in the set-up from figure 8. General corrosive attack on the AISI 310, together with AISI 347 and 12Cr steels, is studied in the KEMA test boiler unit.

Structural degradation (e.g. precipitate coarsening, dislocation mesh growth) and creep cavitation or void formation associated with grain boundaries are the two distinct creep damage processes. In base materials remote from welds structural degradation might be the predominant mode of damage accumulation, in heat-affected zones from welds creep cavitation leading to cracking is the predominant mode of damage accumulation.

The main objective of the investigation at the KEMA metallurgical laboratory will be to quantify cavitation phenomena by several parameters (e.g. amount of voids, void volume, void orientation) in relation to the degree of creep damage and the remanent life expectancy. Figure 9 shows an example of typically oriented voids and carbides on grain boundaries.

Figure 10 shows an amount of voids presented as function of the angle between the longest void axis and the direction of the principal stress.

For quantitative assessments in early stages of creep cavitation a SEM image is necessary. For further quanti- tative analysis the SEM recently has been interfaced with a computerized image analysing system. With this equipment it is possible to study and quantify structural metallurgical parameters in several stages of creep damage.

The quantitative analysis will be related to and compared with remanent life expectations determined by short and longer duration creep rupture tests at elevated temperatures, stress analyses and component rupture tests (e.g. tubes or pipes under internal pressure at high temperatures).

* Figure 5 shows an example which refers to 30 tests on material removed from a 1CrMo steam pipe after 115,000 h of operation at a temperature of approximately 595°C and a hoop stress of 42 MPa. In addition, an excellent reproducibility of the test method is demonstrated.
5.2 ERA PROGRAMME

KEMA, together with other companies from the UK, Denmark, Canada, Japan, the USA, Italy and India, sponsors a project mainly aimed at the verification of the isostress test method. This project consists of three parts. The first part is similar to part B of the KEMA programme. The same tube material (2Cr1Mo) is tested, however under different temperature and internal pressure conditions. The second part is comparable with part A (loading of strips) of the KEMA programme. Instead of 1CrMo and 2Cr1Mo, however, a 1CrMoV steam pipe material and a CrMoV (GS-7MoV5.3) turbine house casting are tested. The third programme consists of loading Ø 38.1x6.4 mm 2Cr1Mo tubes with internal pressure (hoop stress 116 MPa) at 525°C. The failure moment of the tubes is already known under these conditions. After a life fraction of 0.8 the tubes will be rupture tested under the same internal pressure but at elevated temperatures. By extrapolating the test results to 525°C a remanent life fraction of 0.2 should be predicted.

This ERA programme started in 1979 and will probably continue till 1988.

KEMA also sponsors an ERA project which deals with the effect of oxidation on creep rupture strength. Test-pieces*) up to thicknesses of 50 mm are tested in air and argon.

This ERA programme started in 1983 and will continue to 1993.

5.3 NETHERLANDS WELDING INSTITUTE PROGRAMME

The programme of the Netherlands Welding Institute with regard to remanent life mainly consists in loading six new 1Cr1Mo components with outside diameters of 270 mm with and without stress concentrations (e.g. nozzles and wall thickness transitions) under internal pressure at 525°C. They have been designed to give 1 % strain and rupture after 40,000 h. The intention is to load the components for 25,000 h.

Two 1Cr1Mo pipe sections from steam pipe systems of an electricity supply plant and a chemical plant, with 85,000 and 4,380 service hours respectively, are also loaded under internal pressure at 525°C.

Finite element calculations are being performed for predicting the strain behaviour of some components. Destructive and non-destructive metallurgical examinations are periodically carried out for (quantitative) remanent life determinations. The whole programme is accompanied by literature studies.

*) of 1Cr1Mo and 2Cr1Mo

KEMA, together with other companies, sponsors and participates in this Welding Institute programme. The interest of KEMA goes particularly to the quantitative metallurgical examinations, including the merits of isostress tests.

The programme will probably be terminated in 1985.

6 FINAL REMARKS

KEMA is in a fortunate position to base research activities directly on operational practice in power plants, as demonstrated in this paper.

Not yet mentioned is the use of fracture mechanics techniques for predicting the remanent life of components containing defects or cracks. This use can be of interest when a quick start-up of the plant is required where cracks have been detected during inspection. Besides, a weld repair introduces additional uncertainties.

A case is known in which linear elastic fracture mechanics (in accordance with Appendix A of the ASME-Code, Section XI) was used to determine possible crack extension of solidification cracking in a weld from a 1CrMoV steam pipe system, which had been in service for approximately 100,000 h. The system went into operation again without removal of the cracks.

7 ACKNOWLEDGEMENTS

The author wishes to thank especially all his co-workers at the KEMA metallurgical laboratory for their dedication in performing and managing the work described in this paper.
Figure 1
Failure statistic of Dutch power plants from 1960 through 1984 (from Working Group Report 81-31).

Figure 2
Crack types in low-alloy ferritics used under creep conditions.

Figure 3
Creep crack in a 9CrMoV steam pipe system, magnification factor of 50.
stress

minimum, average at temperature T

0.6 x tR

tR

time-to-rupture

0.6 1.0

life fraction

additional inspections required

Figure 4
Philosophy of regulation.

ln tR

Figure 5
Linear extrapolation of 30 iso-stress tests.

Figure 6
KEMA programme for verification of the isostress test method.
Figure 7
Comparison of isostress tests in air and nitrogen with 5% of hydrogen.

Figure 8
Set-up for tube testing with internal pressure and bending load at high temperatures.

Figure 9
SEM image of creep damage in F80Mo with typically oriented voids on grain boundaries and carbides, magnification factor of 4,110.
Figure 10
Example of quantitative assessment of creep cavitation damage.