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Creep damage development in welded X20 and P91

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VÄRMETEKNISK FORSKNING OCH UTVECKLING

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Utveckling av krypskador hos svetsade komponenter av X20 och P91

Steve Brett, Stefan Holmstrom, John Hald, Ulrik Borg, Søren Aakjær Jensen, Rijk Van Vulpen, Craig Degnan, Kristian Vinter Dahl, Tommy Vilhelmsen

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Abstract

The Martensitic steel X20CrMoV121 (hereinafter called X20) and the modified 9Cr1Mo steel (hereinafter called P91) have been used for a number of years in high temperature applications since they posses superiour creep strength compared to low alloyed steels. Due to the simple fact that very few failures were observed, almost no knowledge as to the evolution of creep damage in welds were available despite long operation times exceeding well over 100.000 hours. It has been suggested that X20 will develop creep damage in a different manner compared to low alloyed steel, i.e damage initiation should be slow followed by accelerated growth. The research work presented in this report included systematic investigations of the first components of X20, which has developed creep during long-term operation. All of the investigated components showed creep damage evolution similar to low alloy steels.

Sammanfattning

Fem svetsade formstycken av 12 % Cr-stålet X 20 CrMoV 12 1 (X20) och en svetsad ånglåda av det modifierade 9 % Cr-stålet P91 har undersökts. Dessa material har en utbredd användning i både biobränsle- och koleldade kraft- och kraftvärmeverk. Samtliga undersökta komponenter hade utvecklat krypskador i svetsar under långtidsdrift i upp till 70.000 till 150.000 timmar hos respektive anläggningar.

Syftet med undersökningarna var att etablera kunskap för att kunna upprätta inspektionsstrategier och intervall för återkommande inspektioner för svetsade komponenter tillverkade av dessa stål.

Projektet utfördes i perioden april 2008 till oktober 2010 med RWEnpower E.ON UK, VTT, KEMA, DONG, DTU och Vattenfall Heat Nordic som deltagare.

Ingående granskning av utbytta komponenter från ångledningar tillverkade av X20 visade att krypskador kan förväntas tillväxa på samma sätt som för låglegerade stål. Denna slutsats var ny jämfört med tidigare antaganden. Den huvudsakliga skillnaden mellan den föreliggande studien och tidigare arbeten är att utbytta komponenter fanns tillgängliga för metallografiska undersökningar.

Ett antal metallografiska undersökningar av X20 och P91 visade en kavitetsbildning enligt liknande mönster som har observerats hos låglegerade stål. Det vill säga kavitetsbildning i form av Typ IV skador i den interkritiska zonen av svetsar. Dessutom observerades en avtagande gradient av kavitetsbildning från komponenternas yta mot godsets insida. Det pekar på att krypskadan först bildas vid ytterytan av komponenten. Ånglådan av P91 hade ett ogynnsamt innehåll av Al och N som bidrog till sprickbildningen. Ett tydligt samband mellan N/Al förhållandet och volymdensiteten av MX partiklar stöder denna slutsats.

En gemensam jämförelse mellan ånglådan av P91 från Storbritannien och ett danskt kraftverk utfördes med resultatet att inga skador påträffades i den danska anläggningen hos liknande komponenter (med mer gynnsamma AL/N förhållande). Det indikerar att de brittiska erfarenheterna inte nödvändigtvis behöver vara desamma för P91 komponenter i allmänhet.

FEM analyser har genomförts för att undersöka förtida sprickbildning i en ånglåda tillverkad av P91 från Storbritannien. Både positioner för skadebildning och en kryplivslängd liknande den verkliga kunde förutsägas med hjälp av analyserna. Dessutom visades det att komponentens geometri har stor betydelse i sammanhanget.

En kombinerad kryptöjnings- och krypskademodell baserad på Wilshires krypmodell och Rice och Tracys modell för begränsad kavitetstillväxt utvecklades för X20 och användes för livslängdsbedömning av en ånglåda tillverkad av X20. Modellen visade en god förmåga att förutsäga vid vilka positioner skador och sprickor kommer att utvecklas.

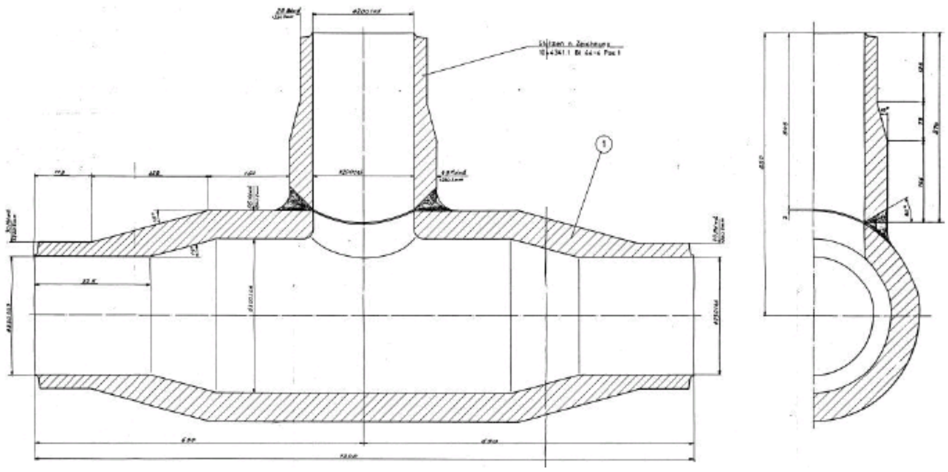
Executive Summary

This chapter contains a concentrated summary of the individual reports which was supplied by the partners.

ASV5 HP-Bypass Branch Connection Component History (DONG Energy, Appendix 1)

Asnæs Power Plant unit 5 was commissioned in 1981 with main steam piping in X20CrMoV12-1 (alloy elements in %: 0,17<C<0,23; 10<Cr<12,5; 0,3<Ni<0,8; 0,8<Mo<1,2; 0,25<V<0,35) fabricated by Mannesmann Rohrbau AG. Nominal operation steam data for the main steam system is 540°C and 180 bar.

The main steam piping includes four welded HP-bypass branch connections.



Welded HP bypass branch connection.

First inspection of the HP-bypass branch connections was in 2002 after 136.500 service hours with inspection of RA11 and RA12. At the inspection of RA11 a small amount of microcracks as well as a small amount of oriented cavities were observed; located at both upper and lower flank position in the branch body HAZ and at one occurrence in weld metal.

Branch connection RA11. Arrows at standard replica position and ground indication.

Re-inspection of RA11 branch weld in 2004 after total 146.000 service hours showed a 40 mm crack indication with magnetic particle testing close to the upper flank position. No indication was observed after 0,2 mm grinding. In the standard upper flank replica position an extensive amount of microcraks and extensive amount of orientated cavities was observed in branch body HAZ. Further grinding showed decreasing creep damage class with extensive amount of isolated cavities in approximately 3mm depth. Lower flank position showed extensive amount of oriented cavities in branch body HAZ.

Additional magnetic particle testing and replica inspection of the other welds at the HP-bypass connections (RA12, RA13 and RA14) showed few additional crack indications with magnetic particle testing which in all cases were removed with maximum 0,2 mm grinding depth. Various levels of creep damage were observed in the inspection; from small amount of isolated cavities to small amount of microcracks.

RA11 followed by RA14 showed the highest level of creep damage in branch weld; mainly in the upper flank position but also with damage development in lower flank position. RA12 and RA13 showed various amounts of isolated cavities in a few positions. Only very few observations with small amounts of isolated cavities were observed for circumferential welds.

No deviant microstructures or hardness were reported.

All four HP-bypass branch connections were replaced in 2005. RA11 branch connection was stored for further investigations, which is reported separately in this Värmeforsk project.

The Danish utilities have a long and good experience with X20CrMoV12-1 for boiler headers, main steam and hot reheat piping. The creep damage levels observed in these branch connections is considered to be the fastest developed creep damage and the first

traditional type IV cracks in X20CrMoV12-1 within this experience. These observations are summarised below:
• RA11 branch weld, lower flank position, developed small amount of microcracks in 136.500 service hours.
• RA11 branch weld, lower flank position, 'decreased' the damage level from small amount of microcracks to extensive amount of oriented cavities in 9.500 service hours.
• RA11 branch weld, upper flank position, developed medium amount of oriented cavities (branch body HAZ) and small amount of microcracks (weld metal) in 136.500 service hours.
• RA11 branch weld, upper flank position, developed from small amount of microcracks to extensive amount of microcracks in 9.500 service hours.
• RA11 branch weld, close to upper flank position, developed magnetic particle testing indications (macrocrack) in 146.000 service hours. These magnetic particle testing indications were developed from no magnetic particle test indications in 9.500 service hours.
• Depth of macrockracks did not exceed 0,2 mm.
• Depth of microcracks is not considered to exceed 1,5-2,0 mm.

The inspection history of these components show that creep damage is easily detected with standard replica technique and classification of damage class according to Nordtest TR 170 and TR 302.

The creep damage development observed in these inspections raise no safety or reliability concerns related to the re-inspection intervals proposed in the Nordtest Project Report VALB211 from 1997 and later issued Värmeforsk project reports.

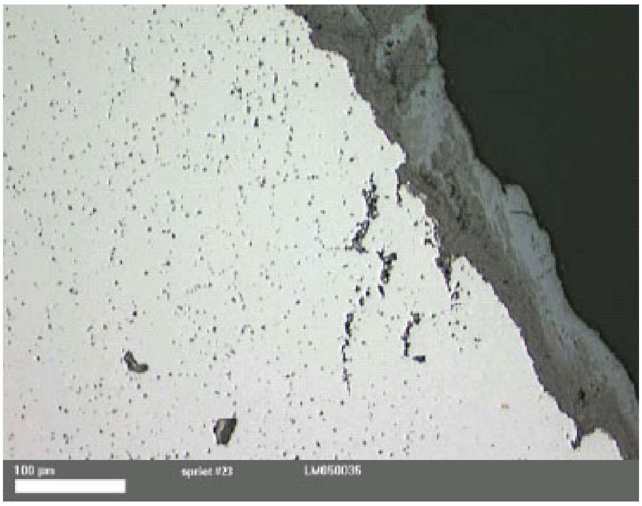
Case histories of creep damage development in welded X20 components (KEMA, Appendix 2)

The KEMA contribution to the project consists of data digging into three cases of creep damaged X20CrMoV12.1 (X20) welded components in Dutch Coal Fired Power Plants. Creep damage occurred after more than 100.000 hrs of operation. Comprehensive documentation of damage evolution from inspection reports and additional analysis are systematized. The three cases are concerning:

(1) Unit MV1 reheater outlet header, 132 khr, 540 °C, 2004
(2) Unit AC8 super heater outlet header,190 khr, 553 °C, replacement intended in 2011
(3) Unit GLD13 super heater outlet headers, 175 khr, 516 °C, replaced in 2007.

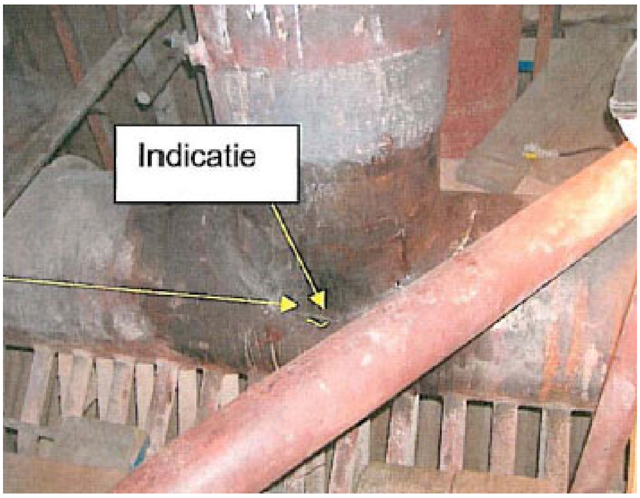
Additional work is done by performing a fitness for purpose analysis program with respect to case (2) and a mechanical testing program of one of the replaced headers with respect to case (3).

Case MV1 shows creep-fatigue damage at the tube side of header-stub connections due to inflexible super heater layout. Selected inspections over the years seemed not to have prevented failure in time.



Cross section at failure location showing creep voids and oxidized crack on the stub side (MV1)

Case AC8 shows that creep damage of welded header-stub connections may develop rather fast at longer operation times. Fitness For Service analysis was needed to estimate relevant re-inspection intervals which have been restricted from 14.000 to 4.000 hrs.



*Crack indications at the header-nozzle connection, nozzle 570 south (Case AC8***)**

Case GL13 shows that creep damage in welded header - stub connections may penetrate from outer surface (damage class 3B) into the header wall up to a maximum of 36% of the wall thickness (damage class 2A) . Fracture toughness of X20 after 175.000 hrs at 516°C is still acceptable 75 J. It is proposed to perform additional creep testing to estimate the residual life time.

GLD13 Header 600, Nozzle 10, side A. Location of samples for testing

Type IV Cavitation Assessment Exercises on an Ex Service Grade 91 Header. (RWE Npower and E.ON UK, Appendix 3)

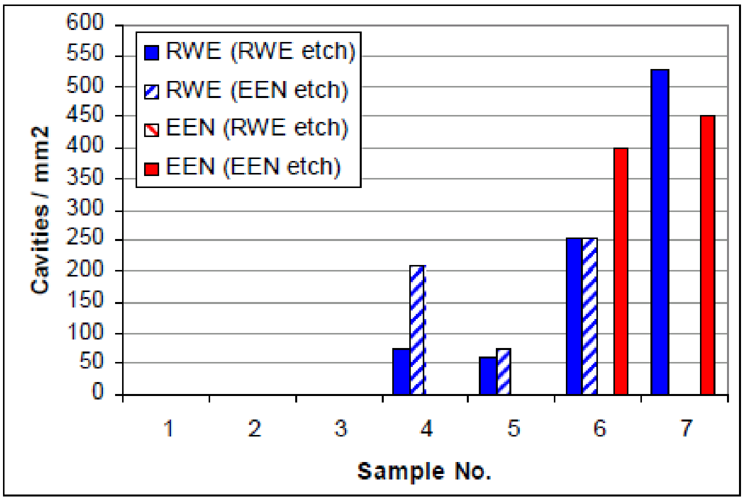
This report provides details of two creep cavitation assessment carried out on an ex service grade 91 final superheater outlet header. The header has been subjected to extensive investigation, both in situ and post service, and its full background history can be found in two published conference papers.

The header was a retrofit component installed on a 500 MW unit in 1992. Early inspection of the header was undertaken because it had been established that a number of low nitrogen to aluminium (N:Al) ratio components had been incorporated in its construction. This had been identified as a factor common to earlier premature plant failures in this grade of steel elsewhere in the UK. Extensive Type IV cracking was found on branch and attachment welds in 2004 after 58Khrs operation and the header was eventually removed from service in 2008 after 79 khrs operation.

The header was designed to BS1113:89 with a design pressure of 17-18 MPa and a design temperature of 580ºC. It was constructed from six ASTM A335 P91 cylindrical barrel sections (450 mm OD x 50 mm t) separated by four ASTM A182 F91 forged T-pieces and a central circumferential butt weld. The ends of the header were closed by forged domed ends and the header was fitted with four ASTM A182 F91 safety valve branches (190 mm OD x 57 mm t), one ASTM A182 F91 main steam atmospheric pass out branch (210 mm OD x 54 mm t), and two much smaller pressure tapping branches. A total of 408 ASTM A213 T91 stubs (54 mm OD x 8 mm t) were distributed along the header body, grouped mainly in 68 elements of 6 stubs (A-F) each. Most of the stubs were attached to the barrel sections with a smaller number on the forged T-pieces. On the barrels the six stubs in each element were arranged at 50º intervals around the circumference between 55º and 305º from top dead centre position. A number of attachment welds were also present, eg main hanger supports and anti-rotation lugs.

Two metallurgical slices were removed from the header section. One slice was taken from the atmospheric passout branch (the largest welded branch on this header) at the header flank position, and another slice was removed from the Barrel 4 to Barrel 3 central butt weld at the header top dead centre position. Only micro graphs from the Barrel 4 side of the centre weld were included in the exercise.

The branch weld section comprised a section of header barrel (pipe), a forged (F91) branch and a Grade 91 fillet weld. The branch was subsequently sectioned into 10 pieces. The pipe butt weld specimen comprised a through-wall section divided into two samples (at the midwall region), one consisting of the top surface and capping bead and the other consisting of the bore and weld root. Both sets of samples were mounted, polished and triple etched for metallographic analysis by both EEN and RWE, and cavity assessments were conducted as a “double-blind” experiment.



Graph comparing cavitation levels measured by EEN and RWE the Type in IV region of the investigated specimens. Note: no values were provided by EEN for RWE etch.

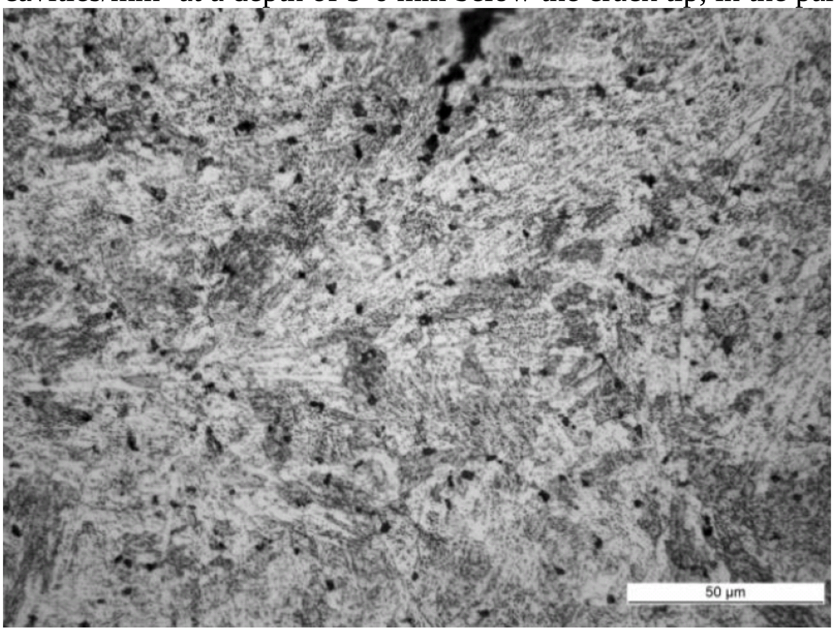
This exercise has highlighted potential sources of errors during the assessment of creep cavitation in Grade 91, particularly from the sample preparation stage, i.e. errors might be induced on further grinding (repreparation) which might reveal/conceal cavities, and from the assessment stage, i.e. errors from counting cavities/features from the manufacturing process (voids associated with globular inclusions, etc.).

Provided care is taken to use a consistent metallurgical replication procedure and assessment methodology, cavitation assessment can be a useful and practical life assessment technique for grade 91 steel. The cavitation levels were broadly similar to those found historically in the older low alloy steels. These older alloys posses a lower creep strength since the alloying level is lower. In particular no evidence was found that grade 91 is less prone to cavitation or that the cavitation is more difficult to detect in this steel.

Creep damage in X20CrMoV11-1 - ex-service experience and a case study (VTT, Appendix 4)

VTT's contribution to the project is a welded X20CrMoV11-1 (or X20) steam header which has been examined after 135.000 h service at 535°C/110 bar. The location of interest is a branch weld showing saddle point creep cracking in the heat affected zone (HAZ) of the header body. The objective was to characterize long term creep damage in a welded X20 component to support guidelines on evaluation of replica inspection results.

The observed creep damage in the HAZ of the branch weld has been severe enough to result in creep cavitation and cavity linking to growing creep cracks. Crack initiation, at least after several times of surface grinding for inspections, has been in the outer HAZ but growth has been mainly across the HAZ towards the parent steel approximately in the longitudinal-radial plane of the header body. The maximum cavity density in the HAZ at the crack tip was about 9000 cavities/mm^2, decreasing to about 200 cavities/mm^2 at a depth of 5-6 mm below the crack tip, in the parent steel.



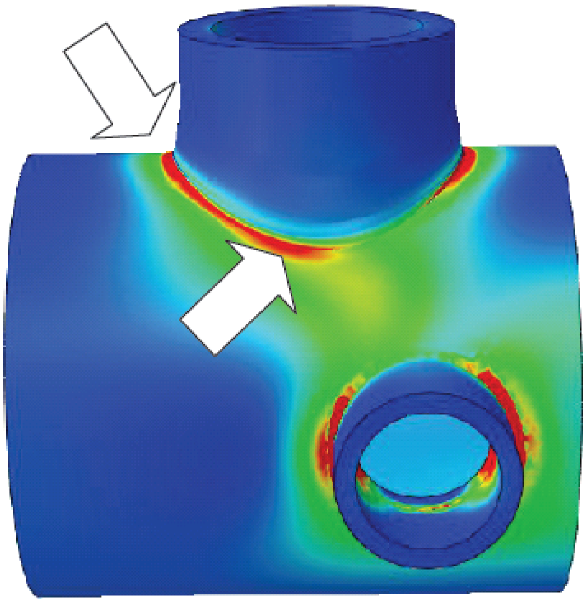
Creep cavitation damage at the crack tip region

The cracks have grown relatively slowly (up to about 1.7 mm in five years, starting from class 3 (orientated cavitation) to 4 (microcracking), and exhibited significant bridging at the front line. It is possible that the growth rate has been slowing down due to the damage progressing across the HAZ into the presumably stronger parent steel.

It has been suggested that creep damage in X20 parent material (e.g. in elbows) would develop very quickly after reaching the stage of microcracking, requiring urgent replacement. However, no creep damage initiating in the parent metal was found in the X20 header of this study. There is a clear difference in the requirements to produce creep damage in welds and parent (ferritic/martensitic) material. In welds the stress-temperature-time combination for creep crack initiation and growth can be expected to be much reduced from that of the parent steel. However, this means that the welds act as mechanical fuses of the piping, and that the evolving damage in welds can provide fair warning in replica inspections well before serious fast cracking can proceed. This was also the experience of the X20 header in this work.

Parameters for the creep rupture and creep strain models presented in this report have been determined by using creep testing data from the public domain. The models accurately describe the time to rupture behavior of X20, as well as the full creep strain response at specified temperature and stress.

The simulation of the 3-D branch weld with the Comsol FEA implementation using logistic creep strain prediction (LCSP) strain model predicted largest strains and extensive creep exhaustion in the HAZ of both crotch and flank positions of the header



Locations of largest creep exhaustion for the branch of interest (arrows);
the impact on the flank position at the "dead end" branch is clearly visible

The multiaxiality filtering technique using the formulation of rigid plastic deformation (based on Rice and Tracey) to describe the developing "creep exhaustion" also indicated increased multiaxial constraint.

The calculated damage (strain exhaustion) can be determined as a function of depth (from the surface) and can possibly be calibrated against measured cavity densities.

Investigations of P91 components at Nordjyllandsværket Power Plant (Vattenfall, Appendix 5)

P91 has been used in the UK for retrofit, mainly for headers. Some of these headers began to develop creep damage after 60.000 hours of operation. P91 is also used extensively at two Danish pulverised fuel power stations, Skærbækværket Power Plant unit 3 and Nordjyllandsværket Power Plant unit 3. The two stations are steaming at 580°C and NJV3 has been in operation for 75.000 hours (summer 2008).

Based on experience with P91 headers from the UK, a model was set up to compare the P91 behaviour in Denmark and UK. Initially a model for P91 was calibrated to give the same life as observed in the UK headers. The next step was to use the same model together with components taken from Nordjyllandsværket unit 3. Doing so it was discovered that creep damage should be present at the Danish plant and in two instances the entire life should have been exhausted after a relatively short period.

	Box		Branch		Operation		Theoretical
	In. Dia	wall	In. Dia	wall			life time
Component	di	Sv	dAi	SA0	T	P	
U8 stubs	350	50	38	8	570	160	60000
U8 safty valve branch	350	50	76	57	570	160	108000
U8 atmospharic pass out branch	350	50	102	54	570	160	70000
Stud exit MOH2.2	480	28	35,5	4,5	600	35	980000
Stud exit MOH1.2	400	60	35	8	600	105	190000
HT2 Collecter	180	65	69	45	585	310	37000
Stud HT2 exit	69	45	20,4	8,8	590	310	128000
Arr.HT1 tube	180	70	38	10	576	310	17600
Arr.MOH2.2	480	28	44,5	4,5	595	25	190000
Exit box MOH 1.1	400	50	31,9	6,3	581	85	583000

A subset of all selected headers both UK and Danish with theoretical life based on a model calibrated so that the calculated lift match the observed life in the UK headers. The three headers above the gray line are from the UK the rest are from Denmark

Because of this it was decided to carry out a non-destructive testing programme at Nordjyllandsværket in the summer of 2008. The two components with the shortest lives were selected for this NDT work performed by FORCE Technology. The investigation showed that no creep damage whatsoever was found. A total of 50 replicas were made of three welds and all microstructures were given a damage level of “Class 1”, which corresponds to no creep damage.

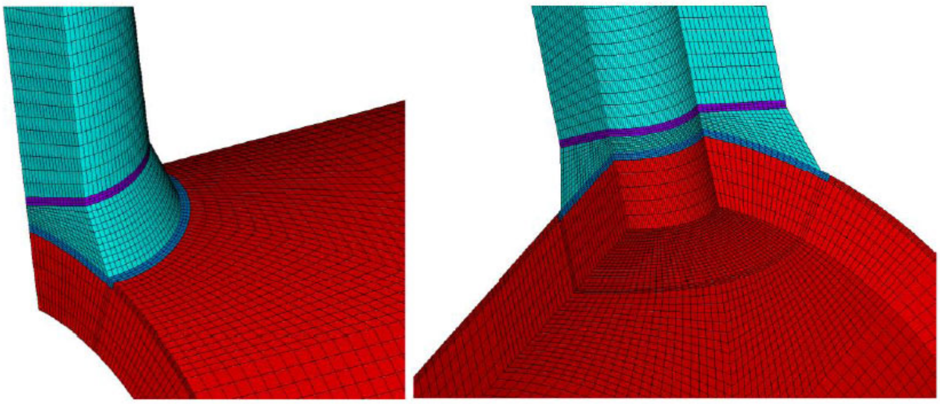
Replication in progress of the collector

This observation leads to the conclusion that the experiences obtained in the UK may not necessary be transferred to other plants. The Al and N content of the Danish headers did not show the unfavourable ratio which was found in the UK headers. This is one possible source for the difference in behaviour.

Creep damage modelling of P91 header and X20 T-joint

(DONG, Appendix 6)

As a contribution to the project, this report describes a relatively simple FE model to predict creep damage in high temperature components. This model is applied to two different cases: 1) A T-joint component of X20 material from Asnaesvaerket described elsewhere in this report. 2) A header/branch joint of P91 material was modeled using the FE method.



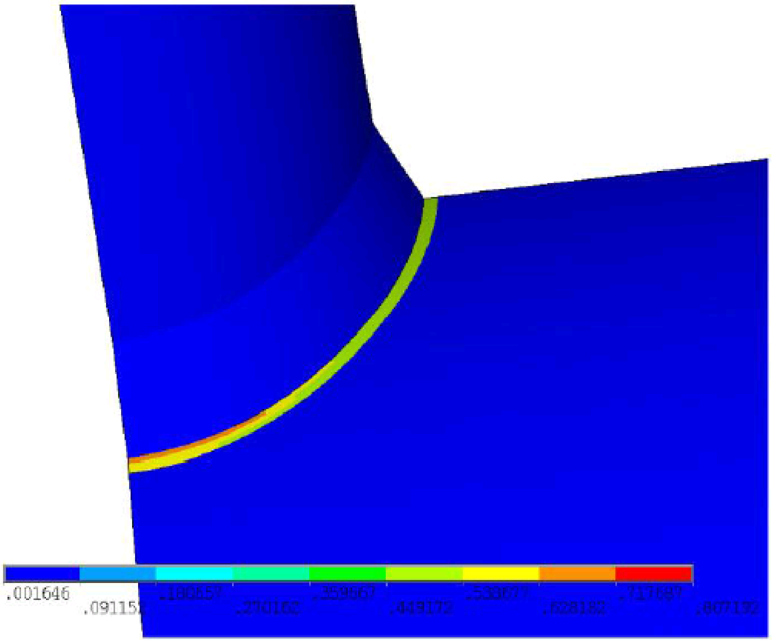
FEM model of the P91 header/branch joint

Both the X20 and P91 components were taken out of service due to extensive creep damage. Hence, the actual creep life is known a priory.

The numerical calculations performed do not predict lifetimes close to the observed life of the X20 and P91 components when standard material parameters are used. That is material data taken from DIN and ECCC.

In the case with the X20 T-joint from Asnaesvaerket there has been no indications in either chemical composition or microstructure that this should be weaker than an average X20 material. However, the calculations for the X20 T-joint showed a creep damage parameter of app. 0.1 after 200.000 hours using an internal pressure load of 180 bar. Using minimum creep rupture data values instead of average values increases the creep damage parameter to app. 0.4 after 200.000 hours. So even with an X20 material in the low creep range the observed creep damage after aprox.150.000 hours could not be simulated with the steam data of 540°C / 180 bar without the introduction of system loads.

The modeling case with the P91 header/branch joint show severe creep damage after 100.000 hours when the header is modeled with weak creep properties. With a minimum creep strain rate ten times higher in the header material than in normal P91, the creep damage parameter was calculated to 0.8 after 100.000 hours.



Creep damage parameter after 100,000 hours with weak header material - outside view.

This level of creep strain rate in the header is considered realistic due to the low N:Al relationship in this component. The model predicted damage initiation in the flank at the HAZ which corresponds closely to the observed position.

Microstructural investigations of X20 and P91 branch connection (DTU, Appendix 7)

<u>X20 header from Asnæs 5</u>
Microstructural investigations were carried out on X20CrMoV12-1 material from the RA11 branch connection in the HPpipe system from Power plant Asnæs 5 (540°C/190 bar). The branch connection was commissioned in 1981. Replica inspections were done in 2002 (136.500h) and 2004 (146.000h). Maximum damage class in the investigated position was 4b (NT TR 302) - followed by re-inspection and 2-step grinding to 3mm depth, which showed 2.3 (NT TR170). The branch connection was removed after ~158,000 hours in 2005. Further background information can be found in the DONG Energy report "Asnæs Power Station, unit 5 HP bypass branch connection - Component history".

Microstructural investigations of the base materials were performed in order to:

- document the weld geometry for use in FEM calculations
- establish whether new damage had developed during the final 11,500 operation hours
- estimate whether the base materials had abnormal creep properties

Microstructural investigation of the bulk materials of the X20 branch connection indicated normal properties of the materials. The weld profile was found to be in accordance with the drawing.

Interestingly creep cavities were found, not in the fine grained zone of the HAZ, but in the zone adjacent to the base material and with the original base material grain structure. The cavities seem to primarily form at prior austenite grain boundaries. The interior of the prior austenite grains are free of cavities but surrounded by grain boundary cavities indicating an intergranular failure mode.

<u>P91 header from RWE Npower</u>
The investigated component is a section of a header that has been in service for 16 years at a power plant operated by RWE Npower in the UK. The header section available for investigations is shown below

Sectioning of branch joint and position of material used for LOM and TEM

The header was replaced in 2008 due to the findings of creep cracks in the HAZ zones of stub and branch welds. The failure occurred long before reaching design life. It was speculated that the premature failure was due to an unfavorable N/Al ratio of the used P91. Studies indicate that the nitrogen to aluminum (N/Al) ratio is very important for the creep properties of the 9% chromium steels, because a low N/Al ratio results in a reduction of strengthening MX particles since the nitrogen is bound in non-strengthening aluminum-nitrides.

From the replica investigations it was found that the observed cavitation behavior in the investigated P91 martensitic structure was similar to that usually observed for the also martensitic X20 material.

The EFTEM (Energy filtered transmission electron microscopy) measurements show good promise, but there are still some issues about accuracy to be addressed in future work. Since the measured precipitate diameter seems to be higher than that measured from extraction replica, a combination of the two methods, where the diameter is measured from extraction replicas and the number of particles per volume is measured by EFTEM may be a very promising tool for measuring precipitate volume densities and phase fractions.

The present EFTEM investigations show that the P91 material from the bulk pipe contains a lower amount (number density, N_v and volume fraction, f_v) of MX precipitates than the material used for the stubs, and two reference materials. This makes it probable that the unfavorable N/Al ratio of the bulk pipe material results in a lower fraction of strengthening MX precipitates.

Material	N/Al ratio	No. of sites	No. of particles	N_V [part/µm^3]	EFTEM fv [%]
Bulk	1.6	19	131	13.2	0.25
Stub	3.3	19	184	26.1	0.32
Ref. 1	1.3	19	148	25.0	0.31
Ref. 2	13.5	18	247	34.8	0.46

Results of image analysis on EFTEM jump ratio images

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Appendices

1 Introduction

1.1 Background

The purpose of the project is to establish knowledge on the long-term creep damage development in welds of real steam power plant components made of steels X20 CrMoV121 (X20) and P91. The knowledge will be used for planning of future plant inspections and re-inspection intervals.

Welded components of the 12CrMoV steel X20 CrMoV121 and of the modified 9Cr steel P91 are investigated with respect to creep damage. All components have developed creep damage in welds during long-term operation up to 70.000-150.000 hours in actual power plants.

The project consortium has access to unique first available components of steels X20 and P91 with well-documented damage evolution histories from long service exposures (70.000-150.000 h) in real plant.

The investigations comprise:

I) Data digging
The comprehensive documentation of damage evolution from inspection reports, etc. will be systematised

II) Characterization of the components
Microstructure investigations of the compontents to map damage and rank materials properties compared to other heats

III) Modeling of damage evolution
FEM modelling of damage evolution based on input from above and calculations on theoretical life under consideration of system stresses

IV) Future implications and inspection strategy
The results from above will be used to set up guidelines for future inspections of welded components. This will be demonstrated with two case studies on existing power plants.

1.2 Description of the research field

General knowledge of creep behavior and damage evolution is used for optimized planning of inspections and replacements of welded components subjected to creep loads. This will reduce the number of forced plant outages due to creep failure in welds. The results can be used to reduce plant operation and maintenance costs by optimized inspections/replacements. The project relates to the Materials and Chemical Technology program on availability and plant life with the goal to reduce total lifetime costs for components and systems with 20%.

The project will supplement the knowledge from earlier Värmeforsk projects:
Krypskador i svetsar av X20 CrMoV 12 1 – Etapp 1.
M4-207, Värmeforsk rapport nr. 809, maj 2003

Krypskador i svetsar av X20 CrMoV 12 1 – Etapp 2.
M4-306, Värmeforsk rapport nr. 874, marts 2004

1.3 Research target and the role within the field

Very little knowledge exists on long-term damage development in steel grades X20 and P91. The objective of the investigations is to establish this knowledge with the purpose to set up inspection strategies and re-inspection intervals for welded components produced in the steels. The project will result in recommendations for inspection intervals, which can be implemented immediately.

There is clearly a lack of knowledge on long-term damage development in these steels as documented in recent reviews under Värmeforsk (rapport nr. 809 and M4 306).

2 Conclusions

This paragraph contains the overall conclusions taking all information of the project into account.

Investigated components:

<u>Components made from X20</u>
A number of distinct features were noted for the failed components:
1) ASV5 branch. Utilization level close to 100%. First creep damage after ~136kh.
2) Branch and main pipe have approximately the same diameter for component AC8.
3) GLD 13 have 2 ¼ Cr weld and branch material ie. a much weaker branch.
4) VTT branch. Utilization level close to 100%. First creep damage after ~100kh.
5) The ASV5 and VTT headers have Ni content in the high end of the range.

<u>Component made from P91</u>
A number of distinct features were noted for the failed components:
1) The investigated P91 headers are good representatives of the retro fit UK headers, both with respect to N:Al ratio and design (branch very thick walled).
2) Tested creep strength is slightly below lower bound values for P91.
3) Uniaxial cross weld estimated life has a spread of four.
4) Comparison from other plant suggest that the UK experience may not necessarily be representative for P91 headers in general.

Inspections
General discussions of the reports led to the following recommendations for inspections of X20 and P91 welds:

Classical Nordtest replica procedure is adequate for both X20 and P91. No special methods are needed for field testing and optical microscopy. No fundamental difference was found in the formation of creep cavitation between the martensitic and lower alloy steels. There is no need to introduce cavity density as measure of creep damage in the martensitic steels, since there was no problem to identify the classical creep damage classes.

The detailed geometry of creep cavities in the martensitic steels may be somewhat different compared to low alloyed steels. For instance cavitations of P91 seems to be more regular.

It has been claimed that martensitic steels does not show creep cavitation before the very end of life, where damage evolution should be fast. This statement is based on very little experience with failed martencitic components. The present work representing a major population of in-service damaged components does not support this claim. Instead, gradual increase in cavitation level over time both for X20 and P91 material was found It is estimated that damage evolution rates are similar to those observed in

1Cr½Mo and 2 ¼ Cr steel. This is based on the present headers which all failed in service prior to the investigations. We therefore look at components having a high life consumption relative to the time in service.

In the X20 header with a 2 ¼ Cr stub the creep damage went from class 1 to class 5 in 32kh. But this was after repair of class 4 damage by grinding. The past history is therefore very important when assessing creep damage of headers which have undergone repair.

Characterization

The most severe creep damage is observed at the boundary between parent material and heat affected zone for both X20 and P91. All creep damage in the investigated components initiated on the surface of the branch weld. A clear gradual decrease in damage level from the surface was observed. This indicate that creep damage initiated at the outside surface. This will not necessarily be true for butt welds.

Investigated X20 material was normal in respect to chemical composition, hardness and microstructure. But the VTT and ASV5 X20 components had Ni content in the higher end of the specification (0,3%<Ni<0,8%).

Particle measurements of the P91 header material showed a low volume fraction of MX particles compared to stub material and reference material with a high N:Al ratio. This confirms the assumption that a materials with low N:Al ratio can have low creep strength.

Modeling

Public domain X20 rupture and strain data were gathered and assessed to formulate strain models for implementation in finite element code. Multiaxial damage filtering used for constraint effect is necessary to predict location of damage. For X20 weld reduction factors have been calculated at 550°C and 600°C.

Damage position and stress redistribution can be predicted. Accurate material parameters are essential for accurate life estimation.

Simulating with lower bound creep values for the header material and average values for the weld and branch material led to a predicted lifetime quite close to those observed. It is estimated that residual stress has relaxed early in life and disappeared by the time of visible creep damage. Weld mismatch will have an influence on rate and position of stress redistribution.

Some system stresses may be necessary to predict failure in the ASV5 X20 component. Elastic calculations of the pipe system do actually indicate that there is an axial tensile stress in the branch which was not included in the model.

Future implications and inspection strategy

The normal care with polishing and etching also has to be observed on martensitic steels.

Nothing was observed to support an initially low damage rate followed by a very high damage rate after the onset of cavitations.

In this project we focus only on correctly heat treated components. Focus should be on utilization level in terms of operating stress and temperature. For improper heat treated material it is recommended to use appropriately more conservative inspection regime

It is recommended to follow VALB211 for identifying time of first inspection.

Regarding re-inspection intervals it is common practice to follow VALB211 recommendations. In an earlier Värmeforsk project (report 874) it is proposed to modify VALB211 to highlight the uncertainty with respect to re-inspection intervals for 12CrMoV before and after 160khs. This criterion was introduced due to lack of information of actual damaged components. Since then a number of cases has come up i.e. those analysed in this report. Our experience does not indicate it is necessary to maintain such a distinction.

For X20 VALB211 recommend shorter re-inspection intervals with damage classes 3a and 3b. compared to 2 ¼ Cr and 1Cr 1/2 Mo steels based on lack of knowledge of damage evolution rates. The present results indicate that similar inspection intervals could be used for X20, 2 ¼ Cr and 1Cr 1/2 Mo steels for damage classes 3a and higher.

In relation to re-inspection intervals for P91, damage evolution seems similar to X20.

In case of repair by grinding only or grinding with subsequent welding it is recommended to identify re-inspection intervals on a case-by-case basis. By "repair" it should be understood a procedure which excavate material to remove cracks not preparation for replication.

Utilization (reserve in the component to withstand system stresses) should be based on actual stress in the flank position and low utilization should be respected to make room for system stresses. This evaluation should be based on design stresses, hence a safety factor also make the evaluation more conservative.

3 Suggestions for future research work

Recommendations for developing a formal equation/procedure for identifying "strange" geometry which does not have the full potential for creep life.

The modeling work can be improved further by optimizations of strain exhaustion formulations, material property determination of heat affected zones by miniature techniques, simulation and verification of multiaxial impact of weld metal (over matched / under matched).

Further work is suggested to develop the predictive capability of the simulation tools. For example, alternatives to the strain exhaustion formulation should be included and the actual HAZ material properties are to be determined. Simulations may need to be performed with over- and undermatched weld metals, and with more detailed description of the HAZ including coarse grained, fine grained and intercritical zones.

Appendices

After this all the individual reports are put in as appendices.

Appendix 1:
ASV5 HP-Bypass Branch Connection Component History (DONG Energy)

Appendix 2:
Case histories of creep damage development in welded X20 and P91 components (KEMA)

Appendix 3:
Type IV Cavitation Assessment Exercises on an Ex Service Grade 91 Header. (RWE Npower and E.ON UK)

Appendix 4:
Creep damage in X20CrMoV11-1 - ex-service experience and a case study (VTT)

Appendix 5:
Investigations of P91 components at Nordjyllandsværket Power Plant (Vattenfall)

Appendix 6:
Creep damage modelling of P91 header and X20 T-joint (DONG Energy)

Appendix 7:
Microstructural investigations of X20 and P91 branch connection (DTU)

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