T73S03 Session 40A: Cracking Mechanisms and Inputs to R5V4/5

Last Update: 10/5/16

Mechanisms which could initiate cracks: R5V4/5 demonstration of insignificant creep or cyclic effects; The end point of a ccg assessment (fracture, collapse, rupture); Define inputs required for an R5V4/5 assessment (plant data, loads, materials data - recap): when can continuous cycling fatigue data be used?; Environmental effects (oxidation-creep-fatigue?); Shakedown, and how cyclic effects would influence a subsequent R5V4/5 assessment.

Qu.: What is the difference between "initiation" and "incubation"

I shall use the terms thus,

- Initiation = creating a crack where there wasn't one before;
- Incubation = the period before a crack starts to grow due to creep (or fatigue).

Confusion sets in when people use "initiation" to mean "incubation". This may be acceptable in an unambiguous phrase such as "after the initiation of crack growth" – which means "post-incubation".

Qu.: When might creep crack growth (ccg) occur?

Obviously operation in the creep temperature regime is necessary to cause ccg. However, to get creep crack *growth*, as opposed to creep crack *initiation*, the following are necessary…

- There must already be a crack, or a sharp feature which approximates sufficiently closely to a crack, and,
- The creep fields near the crack tip must have matured sufficiently for the crack to have incubated.

Qu.: Is there always an incubation period before ccg starts?

No.

It depends upon the mechanism which initiated the crack.

If a creep mechanism caused the crack to initiate, then there will already be a mature region of creep damage around the newly formed crack tip and no incubation period is relevant. Growth occurs immediately after initiation (in fact there is no clear dividing line between initiation and crack growth in this case).

Incubation applies when the initial crack arises from some non-creep mechanism, e.g., an original welding defect or some oxidation/corrosion process.

Qu.: What might cause cracks or features susceptible to ccg?

Almost any feature which is sufficiently sharp for the near-tip fields to approximate those of a true crack will, potentially, be susceptible to ccg. Cracking mechanisms include,

(a) Original sin of many kinds which lead to sharp features, especially welding defects (e.g., lack of fusion, hydrogen cracking, etc);

(b) Reheat cracking;

(c) Type IV cracking;

(d) Fatigue, of many types (e.g., due to service cycles, due to vibration, or thermal fatigue, including TTIBC or small bore refluxing);

(e) Other cracks initiated by creep (e.g., coarse HAZ cracking);

(f) Cracks due to creep-fatigue (cyclic plasticity and cyclic creep);

The above defects/cracks are certainly susceptible to ccg (given the right conditions).

Qu.: Which of the above cracks would have a post-initiation incubation period?

Only (a) for sure.

But also (d) if the cause of fatigue were removed and the issue was subsequent growth by creep.

The rest are all types of creep crack.

Qu.: Are there defects for which susceptibility to ccg is uncertain?

Yes, such as,

- Defects due to IGA (intergranular attack) - aqueous
- Defects due to SCC (stress corrosion cracking) – aqueous or wet steam
- Other corrosion morphology (e.g., pits) – aqueous or damp gaseous
- Intergranular oxide fingers – gaseous (air, CO_2, anything oxidising)
- Fretting damage

Note that fretting damage certainly *does* lead to major cracks propagating by *fatigue*, with the potential for gross structural failure (e.g., generator rotors).

The same is true of SCC, i.e., it can act as initiation sites for subsequent fatigue failures (e.g., LP turbine blade roots).

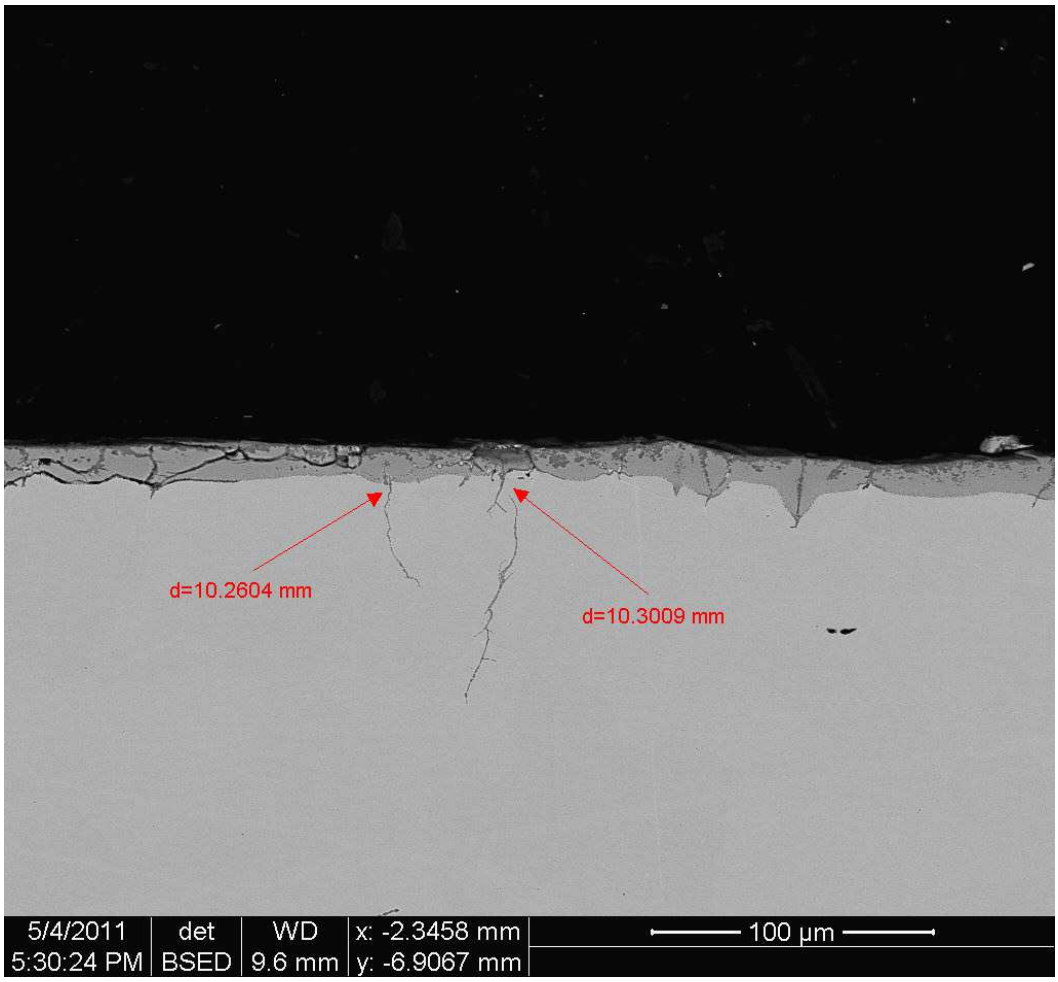
Qu.: Do IGA/SCC defects really grow due to creep?

The issue of whether defects initiated by IGA or SCC can subsequently grow due to creep is very topical, especially in the context of HYA/HRA boilers. I wish I knew whether it is possible or not. These intergranular defects appear sharp in micrographs, so I can see no reason *in principle* for their being immune to ccg.

However, these defects usually occur in closely spaced clusters. This will lead to a reduction in the SIF acting at their tips, due to stress shadowing effects. This can be quantified. Assuming an appropriate SIF, etc, it is difficult to see why standard ccg procedures should not be applicable in principle. The defects would need to incubate first, though, and small defects in a stress shadow will take longer to do so.

If the incubation time exceeds the time to creep rupture the net ligament, then clouds of IGA defects will be equivalent to a net thickness reduction and fracture mechanics assessments are not necessary. Historically this has been assumed without justification. However, incubation assessments for the superheater boilers' austenitic tubing at HRA R2 have provided a justification of this position (Ref.[1]).

Figure 1 Example of IGA Defects
(from chemical clean trials on HYA/HRA 316H boiler tubing)



Qu.: What are "intergranular oxide fingers"?

Gas phase oxidation (e.g. in reactor CO_2) can eat away the grain boundaries in austenitic steels. This is commonly seen in samples removed from reactors or autoclaves after many years exposure. Generally it only affects one or two grains, so the defects are very shallow (typically < 0.2mm) – and, of course, oxide filled. We have a suspicion that this phenomenon arises when the material becomes sensitised This is by analogy with the susceptibility of sensitised austenitics to intergranular attack in aqueous environments. However, the relevance of sensitisation in a gaseous environment is unproved. If true it would suggest a period of time is required before oxide fingers will form, i.e., the material must sensitise first. At ~650°C this will be very quick anyway (months rather than years), but at (say) 540°C it might be many years.

Alternatively oxide fingers might arises from carbide precipitation on grain boundaries, associated with carburisation in a CO_2 environment.

Oxide fingers are unlikely to be of great structural significance in themselves due to their being so shallow. Their potential significance is in acting as initiation sites for subsequent crack growth by fatigue or creep. In this respect there is uncertainty at present, as for IGA/SCC. However, like IGA/SCC, the defects can be sharp. But the

development of a crack-like stress and strain field at their tips might depend upon some plastic straining having taken place (to debond the oxide and allow crack opening). If so, such features may only be a threat if stresses exceed yield. But all this is largely surmise at present.

Figure 2a Intergranular Oxide Fingers due to Accelerated Oxidation in Steam at 650°C for 500 Hours, 316H Boiler Tube (after Serco/TAS/E.000405/R001, Sept.2008)

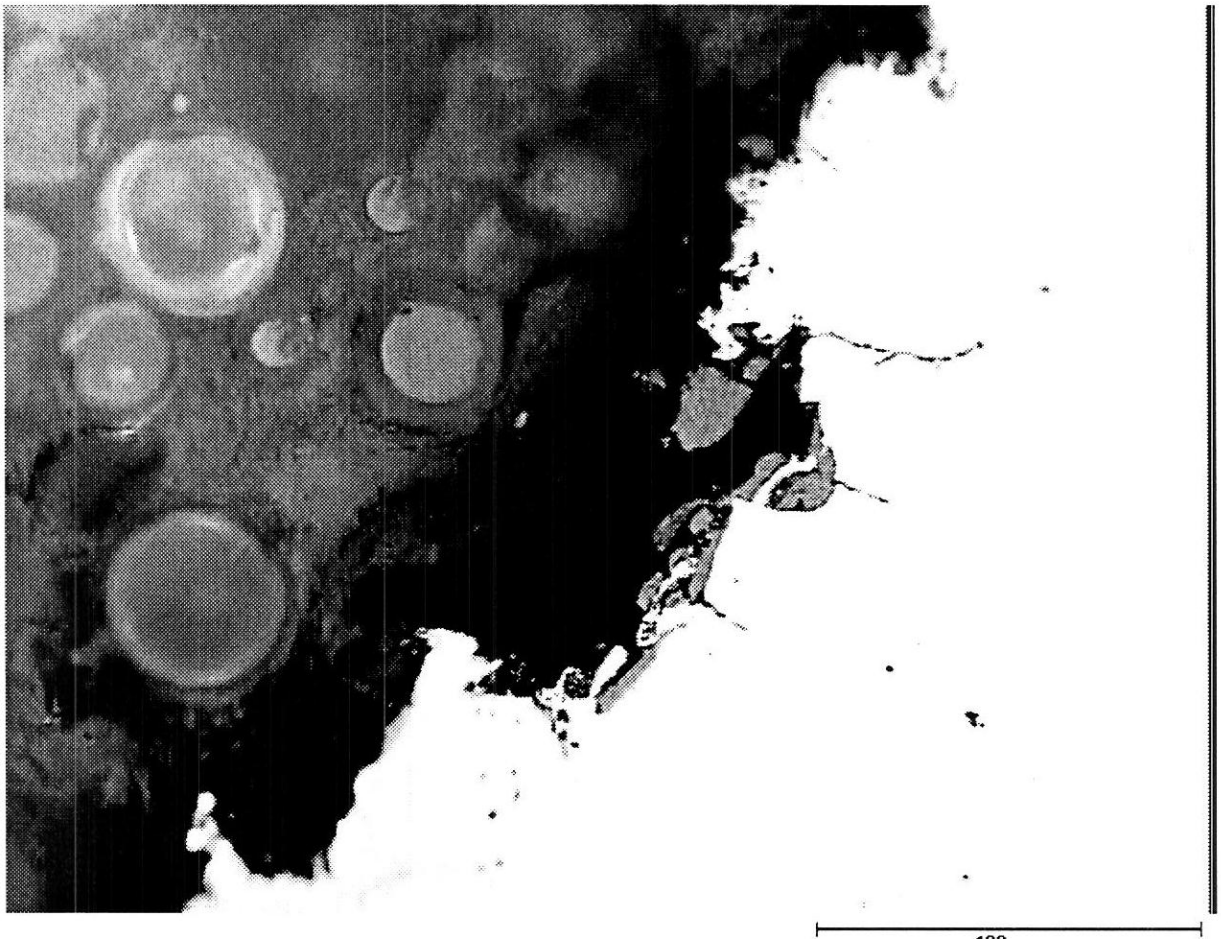
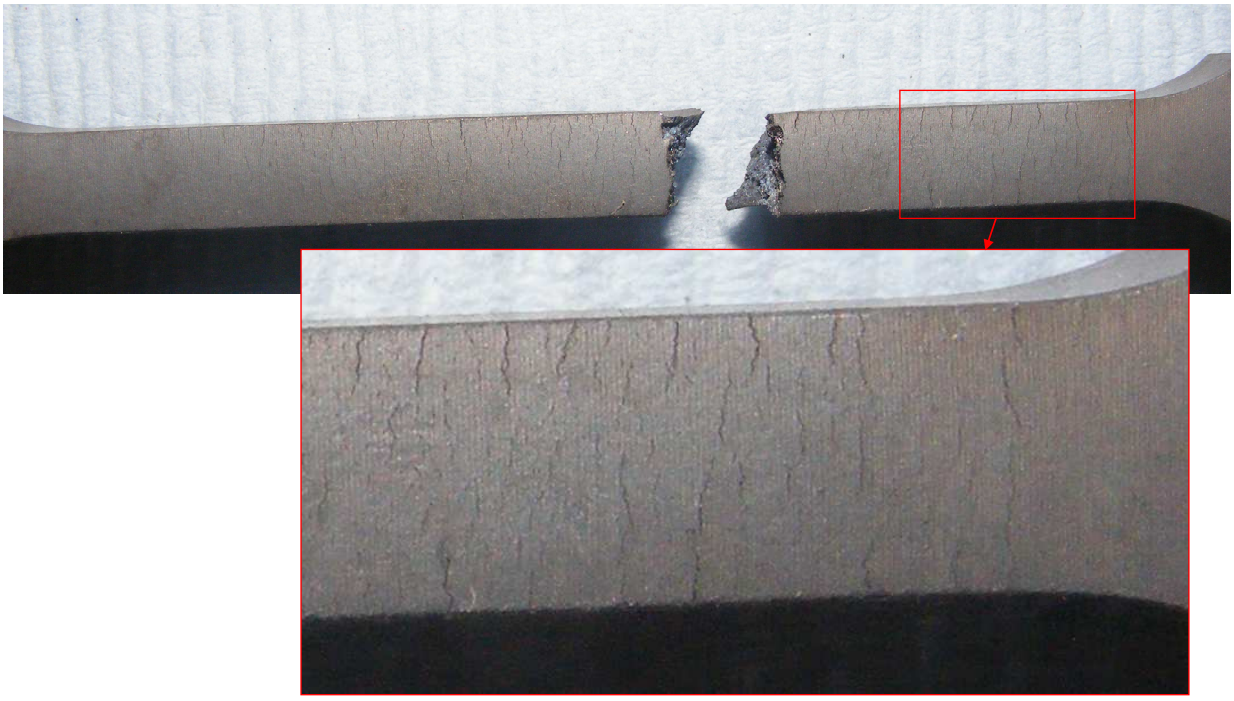


Figure 2b **Ex-Service S/H Tailpipe HNB, Tested in Creep, Showing Extensive Shallow Surface Cracking**

Specimen 5JV, 525C, 280MPa
Outside surface



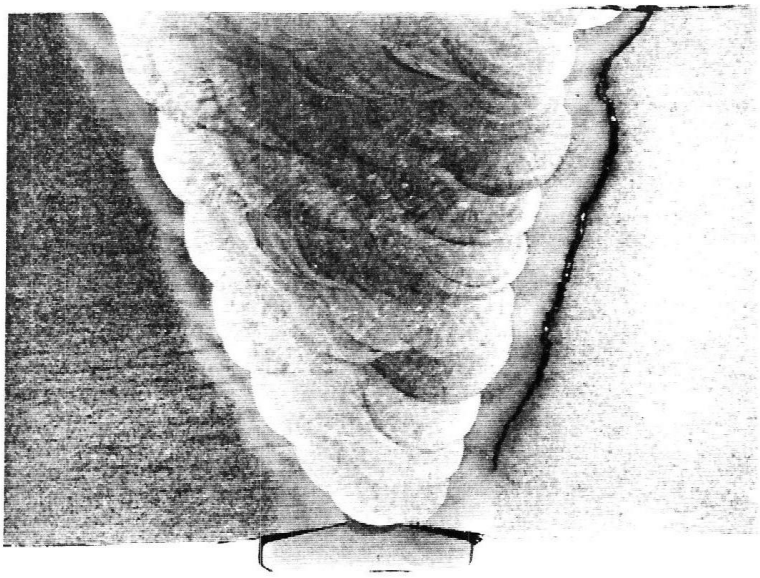
Qu.: What is "Type IV" cracking?

This has been dealt with in detail in session 26 (T73S06), session notes available here,

http://rickbradford.co.uk/T73S06TutorialNotes26.pdf.

It relates to cracking in the inter-critically refined HAZ of low alloy ferritic weldments. It is (one of) the end-of-life creep mechanisms of such weldments. It will occur prematurely if the system stresses are not what they should be – for example, if repairs to the pipework system have been carried out without due regard to maintaining the correct cold pull.

Figure 3: Example Type IV crack in a CMV weldment:-



Qu.: What is "reheat cracking"?

Reheat cracking has been discussed in several previous sessions, e.g., session 27 (T73S06), and sessions 31 and 36 (T73S04), notes available here,

http://rickbradford.co.uk/T73S06TutorialNotes27.pdf

http://rickbradford.co.uk/T73S04TutorialNotes31.pdf

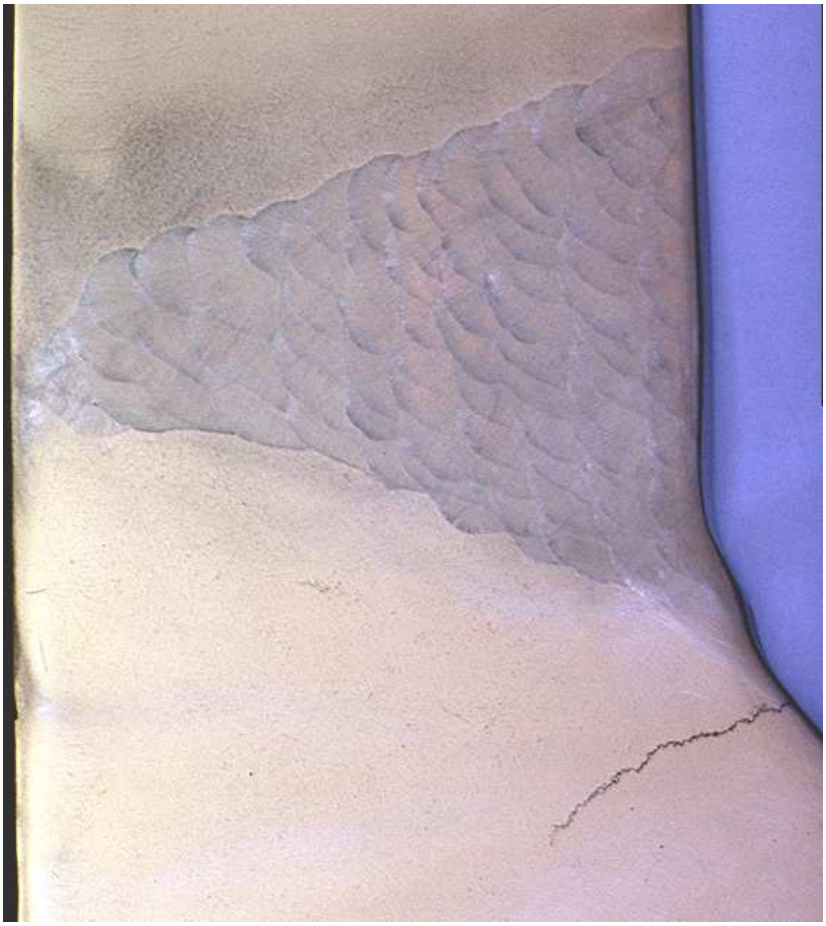
http://rickbradford.co.uk/T73S04TutorialNotes36.pdf

By definition reheat cracking is a type of creep cracking which is driven predominantly by welding residual stresses. It can occur in service only if the weld was not stress relieved. Alternatively a badly conducted heat treatment can itself cause reheat cracking (though it might then be called something else).

Reheat cracking can occur in both ferritic steels and austenitic steels. However it has been rare in ferritics since the late 1970s because design codes call for heat treatment of ferritic weldments. In contrast, the codes frequently (still) permit austenitic welds to enter service without heat treatment. This is the reason why it has been austenitic materials which have been associated with reheat cracking over the last 20 years – not necessarily because they are intrinsically more prone to reheat cracking.

Reheat cracking is an early to mid-life phenomenon. After sufficient time at temperature in the creep regime the initial welding residual stresses will have relaxed and the threat of cracking, if it has not already happened, recedes. The time after which the threat becomes low depends, of course, on the temperature.

Figure 4 Example of Austenitic Reheat Crack (S4 Weld)



Qu.: What is "creep-fatigue crack initiation"?

This is dealt with in detail in sessions 30-38 on T73S04.

Qu.: What types of thermal fatigue crack are there?

<u>TTIBC: Thermal Transient Induced Bore Cracking</u>

This is associated with thick section ferritic pipes and headers. It has been rampant on the main steam systems of conventional power plant since the late 1990s. It occurs on the bore because this is the side where the fluid (steam) changes temperature rapidly.

It occurs on the main steam systems, not the hot reheat systems, because the greater thickness leads to larger thermal stresses. This is a good illustration of the fact that making a structure thicker does not necessarily make it less prone to failure when secondary stresses are the issue.

Although TTIBC in pipework tends to be associated with welds, it is not in the HAZ. It occurs either through the dead centre of the weld itself, starting in the middle of the root run, or, if there is a counter bore, at the angled SCF feature (and hence runs through parent material, well beyond the HAZ). In headers it threatens the ligaments between inlet nozzles/branches.

The mechanism of TTIBC where it actually occurs (conventional plant) is fatigue rather than creep. It is exacerbated in conventional plant by the very high main steam temperatures (>570°C) and large numbers of start-up/shut-down cycles (two-shifting). The higher temperatures cause thermal ageing, which results in a double whammy of poorer fatigue endurance and also softening (and hence increased strain range).

Assessments for TTIBC in AGR systems can appear dominated by creep and can thus be problematical. My prejudice is that this is an artefact of the assessment procedure and/or overly conservative creep ductility data. Such creep-dominated cracking does not align with conventional plant instances of TTIBC, which are fatigue dominated. There have been no cases of TTIBC in AGR plant to my knowledge. An attempt to rationalise TTIBC cracking on conventional plant and make a best estimate assessment of HYA/HRA main steam system is Ref.[2]. However, the use of our usual bounding assumptions often produces a more problematical outcome.

The main lesson we learnt from the experience of TTIBC on conventional plant is that our standard CMV inspection procedures, with their bias towards Type IV cracking, cannot interrogate the bore of the thick section main steam welds. This was news to me (and almost everyone else) at the time. Even now, TTIBC inspections are a special requirement which is only called up occasionally for a few selected welds. (In fact I suspect we've stopped doing any TTIBC inspections). This experience raises the issue of the exact capability of our standard u/t inspections. I'm not sure that we (structural people) know even now.

Header Ligament Cracking

Historically many main steam headers on conventional plant were replaced due to cracking on the ligaments between the inlet branches. This has been a known problem area since the early 1980s. This region can be affected by TTIBC, but from memory I think that simple creep rupture was the problem. As far as I am aware BE/EdF nuclear plant has not had header ligament cracking.

Approximately 10 years ago it became common to replace affected, life-expired headers using P91. This material has high creep strength. Unfortunately its weldment creep properties are crap. Type IV cracks have become rampant in replacement P91 items in a horribly short period of time. BE/EdF nuclear plant remains P91-free (I'm not sure about West Burton and Cottam).

Thick Section Thermal Fatigue Cracking

The classic location of thermal fatigue cracking on two-shifting conventional plant is the inside of steam chests. These very thick castings are particularly susceptible. (Note, once again, the thicker the section, the more susceptible is the component to thermal transient induced cracking). It is not really different in kind from TTIBC, though it has been a known problem for longer. It can get so severe that bits break off (spalling). Unlike main steam pipes and headers, though, the primary stresses in steam chests are generally small due to their very thick section. Consequently the classic phenomenon is a mess of internal cracking but without cracks progressing to become leaks. They tend instead to a limiting depth and stabilise. This is the distinction from TTIBC in pipes/headers where high pressure and/or system stresses drive cracks to become leaks, with the potential to ultimately cause gross failures. Mitigation is to ameliorate the transients. BE/EdF nuclear plant has not had such cracking to my knowledge, due to less severe transients and far fewer of them.

Small Bore Branch Thermal Fatigue Cracking

Small bore branch thermal fatigue is better called "condensate reflux cracking". It is an interesting mechanism because it is a case of fatigue when the gross plant operation is steady. It occurs in main steam or hot reheat lines where they have small bore branches. It is caused by a build-up of condensate within the small bore lines. This condensate is at a much lower temperature than the main run pipe. If the condensate periodically gets sucked back into the main run pipe ("refluxes") it will thermally shock the bore of the branch. This causes very characteristic cracks at the branch/main junction. The cracks are radial to the branch and are opened by the branch hoop stress caused by the thermal shock.

The mechanism can only occur if the small bore branch line is permitted to drop to temperatures below the saturation temperature, so permitting condensation. If condensate forms, and if there is nothing physical to prevent refluxing (e.g., a valve), then refluxing is virtually inevitable. This is a very virulent mechanism because it can cause large numbers of thermal fatigue cycles very quickly. I am not aware of a formal assessment but my informal investigation of how to quantify the mechanism is here http://rickbradford.co.uk/SmallBoreThermalFatigue.pdf.

One does not normally attempt to assess ones way out of such a problem. The correct response is to stop the condensation/refluxing happening. Mitigation is provided by ensuring that any small bore lines which could encourage condensation are lagged (preferably under the main line lagging) to keep them too hot to result in condensation. Alternatively, in some cases it may be possible to close valves to prevent condensate refluxing back to the main line – or to open valves to ensure that condensate drains away safely rather than refluxes. The decision depends upon the particular plant configuration.

Qu.: Are there any other fatigue crack initiation mechanisms?

Most obviously there is creep-fatigue cracking, the initiation of which is the subject of T73S04 (R5V2/3), for which see sessions 30-38.

There is also high-cycle fatigue (vibration). This is beyond the scope of R5 and is addressed by R2. Some issues of relevance have been discussed in session 35 here http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

Qu.: What is the criterion for insignificant creep in R5V4/5?

The criterion for insignificant creep in uncracked structures was discussed in session 23, see http://rickbradford.co.uk/T73S06TutorialNotes23.pdf. But...

Warning: The criterion for insignificant creep is different for cracked and uncracked structures

For cracked structures, the test for insignificant creep is defined in R5V4/5 §9.1 and Figures A6.6 and A6.7 in Appendix A6.

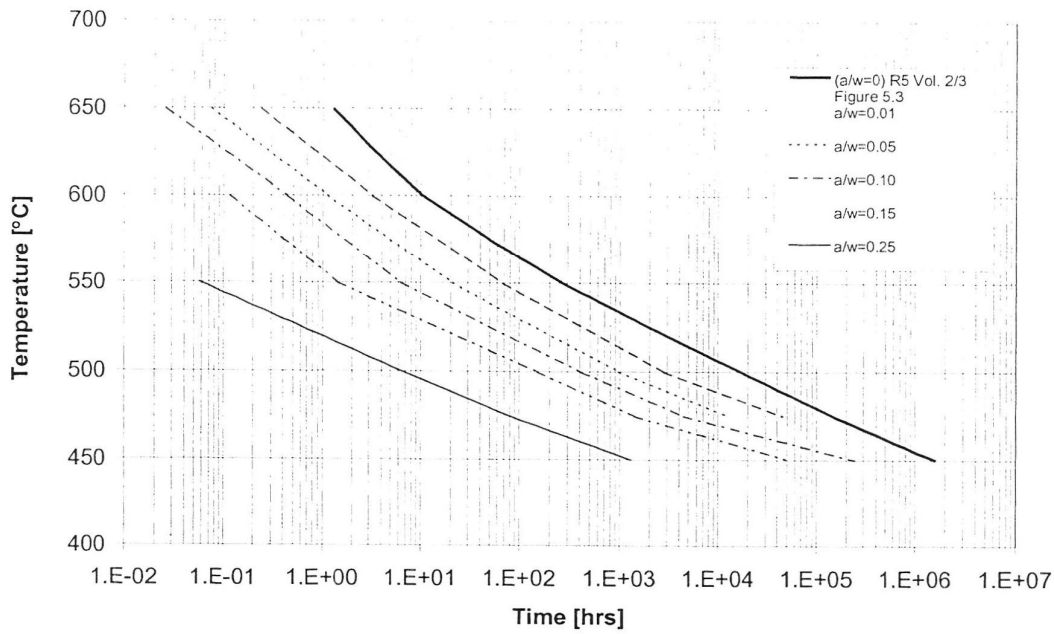
For cracked structures, the (in)significance of creep depends upon the crack depth. The criterion is that creep is insignificant for a period of time t_m defined as the time to accumulate a strain equal to 1/50th of the creep ductility (capped at 10%) at the relevant ***reference*** stress and operating/assessment temperature. (In addition, t_m is limited to the LOIC time for the uncracked structure). The use of the reference stress

in the definition of t_m is what causes the crack size dependence.

Unlike the uncracked LOIC, t_m depends upon the loading of the structure. However, for 304ss and 316ss, Figures A6.6 and A6.7 in R5V4/5 Appendix A6 give load independent versions (essentially generalisations of LOIC to the cracked case). The 316 curve is given as Figure 5 below.

For example, for 316 the uncracked LOIC for 250,000 hours is ~470°C, whereas for a structure with a 10% crack it drops to ~450°C, and may be little more than 400°C for a 25% crack.

Figure 5 Insignificant Creep for Cracked 316 Sections



e A6.6 Negligible creep curves for cracked sections of 316L(N) less than 50mm thickness, with varying crack depth to section thickness ratios (these curves can be used for all 316 stainless steel materials)

Qu.: What are the criteria for insignificant cyclic loading in R5V4/5?

The criteria are in two parts, for the gross behaviour when assumed uncracked and for the crack tip region.

For the gross, uncracked structure, the criteria are given as in R5V2/3 Section 6.6.2. This aspect of cyclic loading may be deemed insignificant if all three of the following criteria are met,

- The greatest elastic Mises stress range, $\Delta\bar{\sigma}_{el,\max}$, is less than the sum of $K_S S_y$ at the two ends of the cycle;
- The elastically based fatigue damage is less than 0.05;
- Creep behaviour is unperturbed by cyclic loading.

The crack-dependent parts of the checks for insignificant cyclic effects are,

- The fatigue crack growth does not exceed 10% of the creep crack growth, and,

- The cyclic plastic zone at the crack tip is small compared with the characteristic dimensions (i.e., the crack size, the ligament size and the thickness).

The cyclic plastic zone size is given by,

Plane Stress: $$r_p = \frac{1}{2\pi}\left(\frac{\Delta K}{2\sigma_y}\right)^2$$

or 1/3 of this in plane strain, where σ_y is the cyclic yield strength (0.2%). All five of the above conditions must be met for cyclic loading to be insignificant.

Personally I would add the requirement to be within strict shakedown to this list. I suspect that the first criterion, above, namely $\Delta\bar{\sigma}_{el,\max} < (K_S S_y)_c + (K_S S_y)_{nc}$, is intended to ensure this – but actually this criterion is *not* sufficient to ensure strict shakedown.

Qu.: Should fatigue crack growth (fcg) data with dwells be used?

This is a very important decision because fatigue crack growth laws based on tests which include dwells at creep temperatures can be far more onerous than those based on continuous cycling tests (e.g., by about an order of magnitude – compare R66 Sections 10 and 12). In practice the fcg laws based on continuous cycling are more commonly used because the R5V4/5 assessment itself takes account of the ccg part separately.

However, R5V4/5 §9.3(i) specifies an exception. This is when creep is perturbed by cyclic loading but the fcg is less than 10% of the ccg. In this case the use of fcg data based on tests including dwells "relevant to the service application" is recommended. Given that service dwells are likely to be of the order of 1000 hours or more this will be problematical! However, the use of R66 Section 12, as a minimum, appears motivated.

Qu.: Are there any other interactions between creep and fcg?

Potentially, yes.

In principle the fcg rate can be accelerated through material previously damaged by creep [see R5V4/5 §9.3(ii)]. One school of thought is that this is relevant only for very heavy creep damage, i.e., if $D_c > 0.8$ (BS7910). Another is that fcg should be factored by $1/(1 - D_c)$ at all damage levels. In either case my opinion is that the D_c in question should be a best estimate.

Tests conducted at Bwd100 to investigate the effect of prior creep damage on fcg (and toughness) have proved tricky to interpret. Growth can be accelerated significantly, but I'm not sure if this effect persists to large amounts of growth (i.e., beyond the prior damaged region). *Latest position?*

Qu.: How is the stability of the crack ensured?

By using R6, of course.

When performing a crack growth assessment the end point will be when the crack becomes unstable. This might be required to be under some fault condition (despite the crack growth being carried out for normal operating conditions).

Qu.: What materials data are required for an R5V4/5 assessment?

A lot! This must include the requirements of R6 as well as the inputs of R5V4/5 itself. The required material data are listed in R5V4/5 §7 with further details in Appendix A1. In summary they are,

[1] Elastic moduli, E, ν;

[2] The lower bound 0.2% proof strength and UTS (for R6 and for the shakedown assessment), and the whole monotonic stress-strain curve if the sigma-d incubation procedure is used;

[3] Fracture toughness;

[4] The shakedown factor, Ks;

[5] A cyclic stress-strain curve (to determine the cyclic plastic zone size around the crack tip as well as for constructing the hysteresis cycle, if relevant, and also potentially required in a sigma-d incubation assessment). The distinction between the cyclic and monotonic stress-strain curves is discuss in http://rickbradford.co.uk/T73S04TutorialNotes31.pdf;

[6] Creep rupture data/equation;

[7] Creep deformation data/equation, including the creep index, n;

[8] Creep ductility, including its dependence on strain rate and stress triaxiality, and possibly dwell stress (to assess ligament rupture via ductility exhaustion and possible for a Method II creep-fatigue crack growth law, which uses D_c at the surface);

[9] For incubation assessments, either (i)critical incubation CTOD; or, (ii)creep toughness if the HTFAD is used (though this can be approximated from the ccg law); or, (iii)fatigue endurance if sigma-d is used (in addition to creep rupture).

[10] Creep crack growth law;

[11] Fatigue crack growth law (Paris Law or small crack law, as appropriate);

I do not guarantee that the above list is complete. (You might require stress-strain specific to a weldment, for example).

Qu.: What other input data are needed for an R5V4/5 assessment?

In addition to materials data, the other main inputs to an R5V4/5 assessment relate to the operating conditions and the idealisations to be employed. Some of these are,

- The historical temperatures, most conveniently expressed as an historic MECT (generally a best estimate);
- The projected future operating temperature, also most conveniently expressed as an MECT (generally a best estimate with a slight conservative bias);
- Normal operating loads (for creep);
- The peak normal operating loads (maximum and minimum) defining the fatigue cycles;
- Fault loads for the crack stability (R6) assessment;

- Past and projected operating hours;
- Past and projected cycling rate;
- Load categorisation (primary or secondary);
- Defect size, shape, position and orientation (actual or hypothesised);
- Material/weldment zones in which cracks occur or are to be postulated;
- Elastic follow-up factor(s), Z.

Qu.: How might Z differ from that used in R5V2/3?

There are two (potentially) significant differences between the Z used in R5V2/3 and that used in R5V4/5:-

[1] The R5V2/3 Z refers to the stresses and strains at the point being assessed for crack initiation, e.g., a surface point. In R5V4/5 the Z is used in the equation specifying the relaxation of the reference stress. Hence the relevant Z in R5V4/5 relates to the gross section, i.e., the reference stress.

[2] The R5V2/3 Z refers to the uncracked structure whereas the R5V4/5 Z refers to the cracked structure. The presence of the crack will generally increase the effective Z (at least for points near the crack tip, but this is not so clear as regards the gross ligament).

In the absence of better information, R5 Issue 3 (2003) advises that the uncracked Z be increased by 1 for an R5V4/5 assessment.

However, the current view is that in many cases the Z to be used in R5V4/5 need not exceed that which would be used in R5V2/3. In fact, I would argue, that if there is a surface stress raiser which elevates the value of Z relevant to a crack initiation assessment, then the Z appropriate in R5V4/5 might actually be smaller. See R5V4/5 Appendix A3, §A3.5.1 for further discussion.

Qu.: How is cyclic stress-strain behaviour modified by service exposure?

This was discussed in http://rickbradford.co.uk/T73S04TutorialNotes31.pdf. A very rough guide is,

- Materials may cyclically harden (typical of austenitic parent) or cyclically soften (typical of austenitic weld material or ferritic parent material, but not invariably). This effect should be implicit in the cyclic stress-strain curves used in your assessments – though this may depend upon whether they have been derived over a number of cycles comparable with the plant application. Note that austenitic materials often slowly cyclically soften once they are passed peak hardening.
- Materials may thermally harden or soften. Thermal softening of low alloy ferritics at ~570°C may be implicated in TTIBC on conventional plant.
- Even for a given number of cycles, the cyclic stress-strain curve may be dependent upon the duration and temperature of the creep dwells. For example, long dwells will reduce the cyclic hardening experienced by austenitic parent materials. Guidance on how to allow for this is given in R66 Section 8.6. However, this guidance is poor in my opinion, as is that of R66 Section 8.7 relating to cycle evolution - see the Recommendations in report E/REP/BBAB/0022/AGR/12 and seek advice if you are thinking of accounting for cycle evolution of long dwell effects on cyclic hardening.

Qu.: What is the relevance of strict shakedown or global shakedown?

The methods for assessing whether a structure is in strict or global shakedown have been dealt with in http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

The cfcg procedure of R5V4/5 is valid only if the structure is within either strict or global shakedown.

If the structure is within global shakedown but outwith strict shakedown then cyclic loading is significant (according to the test defined above). A number of aspects of the cfcg procedure are specific to significant cyclic loading…

Qu.: What parts of the cfcg procedure are required only for significant cyclic loads?

The parts of the cfcg procedure which are specifically required for significant cyclic loading but not otherwise are,

§10.6 Time to reach steady cyclic state and §10.7.1.3 Growth prior to steady cycling

R5V4/5 includes a procedure in these sections for estimating the time to reach the steady cyclic state, and then to estimate the crack growth during this transient phase. The method requires the reference stress to be calculated both for the first cycle and for the steady state cycle.

§10.7.3.2 Method II crack growth law

If cyclic loads are significant then it might be that the crack is fully contained within the cyclic plastic zone. If so, then Method II must be used for estimating crack growth. This is based on,

- The short crack fcg law: $\left(\frac{da}{dN}\right)_f = B'a^Q$ rather than a Paris Law;
- A total crack growth using: $\frac{da}{dN} = \frac{1}{\left(1 - D_c^{surface}\right)^2}\left(\frac{da}{dN}\right)_f$ rather than a C(t) based ccg law - see §10.7.3.2 for details

Appendix A3 Cyclic Loading

The procedure for estimating the crack growth (including the ccg part) differs from that for steady creep in Appendix A2. The details are too numerous to go into here but will be treated in detail in a later session.

Qu.: What provisions in R5V4/5 address displacement controlled loads?

Appendix A3 caters for cfcg under combined loading. For example, §A3.4.3 includes relaxation of the initial reference stress due to creep and also treats primary and secondary stresses differently in the estimation of the C(t) parameter (see for example Equ.A3.19). The treatment of combined loading in respect of C(t) estimation and the associated relaxation effects was originally devised by Ainsworth, Dean & Budden, Ref.[3], but this methodology was introduced into R5V4/5 (Issue 3) in 2012.

There are also specific means of catering for secondary loads in the high-temperature failure assessment diagram (HTFAD) methodology of Appendix A5 and the sigma-d incubation methodology of Appendix A6.

All these methodologies will be discussed in more detail in later sessions.

Qu.: Which material properties may be affected by high service temperatures?

This has been addressed in other sessions.

Qu.: Is the distinction between creep brittle and creep ductile behaviour relevant?

Yes. Appendix A1 says, "*It is commonly observed that creep rupture ductilities decrease with increasing test duration as intergranular cavitation increasingly dominates the failure mechanism. In crack incubation and growth tests, the multiaxial stress state ahead of a crack promotes low displacement failures. For materials which cavitate readily such mechanisms may be reproduced by testing at higher stress levels. However, in materials where the low stress mechanism is replaced by matrix deformation dominated failure at higher stresses it may be necessary to accelerate tests by increasing temperatures rather than stresses. In either case, it is essential that the mechanisms operative in the test specimen lead to failures at least as brittle as those which would occur under service conditions*."

The criterion for creep behaviour to be brittle is given in R5V2/3 Appendix A1, §A1.7 (ductility less than 5 x the product of minimum creep rate and time to failure).

References

[1] R.A.W.Bradford, "Creep-Fatigue Crack Growth Incubation Assessments of IGA Defects in the Boiler Secondary Superheater Tailpipes and Bifurcations, Hartlepool R2", E/EAN/BBAB/0025/HRA/11.

[2] R.A.W.Bradford, "Hartlepool/Heysham I: Implications of Main Steam Pipework Thermal Fatigue Cracking Observed at Coal Fired Power Stations for Heysham I and Hartlepool AGR Power Stations", E/REP/STAN/0149/AGR/02, May 2002.

[3] R A Ainsworth, D W Dean and P J Budden, "Creep and Creep-Fatigue Crack Growth for Combined Loading: Extension of the Advice in R5 Volume 4/5 Appendix A3", E/REP/BDBB/0059/GEN/04, Rev.003, May 2010. Included in R5 Issue 3 in 2012.