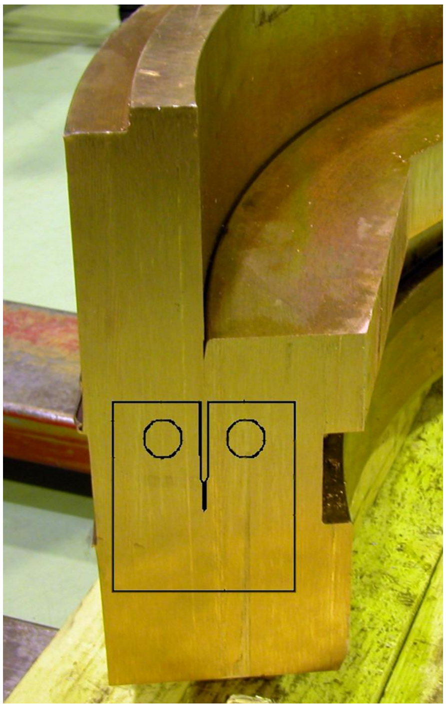
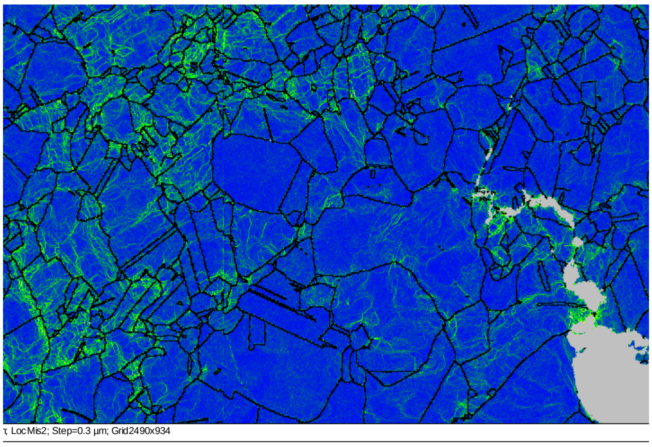
RESEARCH REPORT

NO VTT-R-01581-11
28.2.2011





KYT 2010 / PIKE

Long-term integrity of copper overpack
–Final report 2010

Authors: Juhani Rantala, Jorma Salonen, Pertti Auerkari, Stefan Holmström / VTT
Tapio Saukkonen / Aalto University

Confidentiality: Public

Report's title

Long-term integrity of copper overpack – Final report 2010

Customer, contact person, address KYT 2010	Order reference
Project name PIKE	Project number/Short name 41802
Author(s) Juhani Rantala, Jorma Salonen, Pertti Auerkari, Stefan Holmström / VTT; Tapio Saukkonen / Aalto University	Pages 28
Keywords creep, corrosion, copper, repository, life	Report identification code VTT-R-01581-11

Summary

Microstructural changes in base material and FSW welds of OFP copper have been explored during low temperature (150-175°C), low stress (35-120 MPa) creep experiments. The observed changes in the multiaxial (CT) specimens tested up to 30000 h (3.4 years) at 175°C appear to be largely restricted to widening recovery zones at stressed grain boundaries and to increasing of grain boundary cavitation at the natural (joint) notch tip. The cavitation damage appears to be related to the combined local strain and stress state in front of the notch/crack tip.

Creep cracking with very low ductility was confirmed in pure (OFHC) copper tested up to 10400 h (1.2 years), while much higher creep ductility has been retained in OFP copper so far. The longest continuing uniaxial creep test for OFP copper (150°C/120 MPa) has exceeded 75000 h (8.5 years) but shows increasing surface cracking on the specimen. The results have been used for approximate life assessment with the latest expected temperature history, different assumed stress levels, and the material creep model of the Wilshire type. The resulting predicted allowable (constant) stress level would be about 140 MPa for the copper overpack.

In the combined corrosion and creep testing with welded CT specimens immersed in aerated simulated Olkiluoto groundwater at 90°C, heavy general corrosion up to a depth of about 2 mm was observed after only 4400 h of testing. So far no significant indications of localised corrosion have been observed. Recommendations are given on future work.

Confidentiality	Public

Espoo 28.2.2011

Written by	Reviewed by	Accepted by
Juhani Rantala Senior Research Scientist	Juha Veivo Research Scientist	Pentti Kauppinen Technology Manager

VTT's contact address

POB 1000, FI-02044 VTT, Finland; email firstname.surname@vtt.fi

Distribution (customer and VTT)

KYT	2 copies
VTT	2 copies

Preface

This report provides the final report of the project “Long term integrity of copper overpack” (PIKE), including and summarising the experimental, modelling and life assessment activities as well as the results and status of the project up to end of 2010. The project is a part of the Finnish national research program on nuclear waste management, 2006-2010 (KYT2010). The financial support by this program is gratefully acknowledged.

Espoo, February 28, 2011

Authors

Contents

1 Introduction

1.1 Background

The technical challenge in assessing the integrity of the spent fuel copper overpack is the discrepancy between the longest achievable laboratory test times compared to the design life which is of the order of glaciation cycles to reduce the radioactivity of the contents close to the background level. This timescale far exceeds the normal allowable limits of extrapolation from laboratory experiments to real conditions.

The current concept of managing spent nuclear fuel in Finland and Sweden involves encapsulation of the fuel in metallic canisters that are placed into a deep underground repository [1]. The required design life is of the order of glaciation cycles to reduce the radioactivity of the contents close to the background level. The temperature of the canister is expected to peak at about 90°C during the first 1000 years, with gradual cooling to the level of the bedrock environment. For the protective copper (Cu-OFP) overpack of the canister, creep and corrosion are included as potential damage mechanisms under the repository conditions [2, 3]. Although relatively mild in usual engineering terms, the repository conditions imply a significant challenge to the life estimates for such damage mechanisms, as the expected design life is one to four orders of magnitude longer than for ordinary engineering structures designed against these mechanisms.

This work is dealing with both damage mechanisms in an effort to provide a realistic model for life prediction and long term behaviour of the copper overpack. This research particularly includes

- assessment of damage mechanisms and their interaction: primary creep, damage interaction in groundwater, impact of oxidation and thermal degradation
- material and life modelling of creep, damage and corrosion, and their combined action; and
- evaluation of long term materials properties of the welded copper overpack, and the expected impact on the overpack life in the repository.

The project is a part of the Finnish national research program on nuclear waste management 2006-2010 (KYT2010). The project also includes specific issues requested and defined by SSM (formerly SKI, Sweden).

1.2 Objectives

The principal objectives of the project are

- to determine experimentally and model the long term mechanical (creep) behaviour of the copper overpack, including effects of low stresses, multiaxiality, defects and reduced ductility; and

- to determine experimentally and model the combined creep/corrosion impact of the expected oxygen potential transition on the predicted life of the overpack.

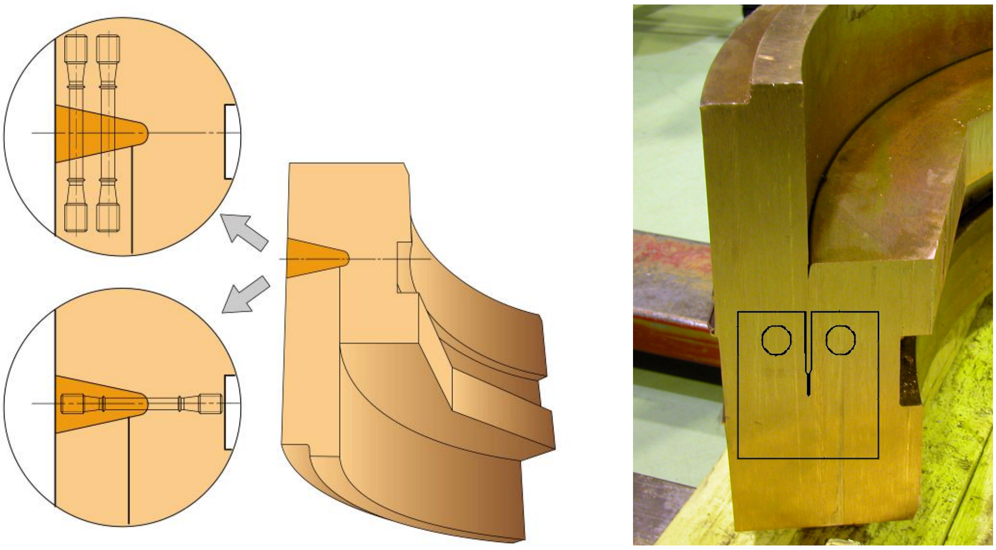
The particular technical objectives for the year 2010 have been:

- to extend the combined creep and corrosion damage modelling for efficient and robust life prediction; and
- to apply new life models in FEA and long term material behaviour for justified life prediction of the overpack copper.

2 Materials and methods

The OFP copper material for the experiments on the friction stir welded (FSW) test material was obtained from a full scale section provided by SSM/SKI (Sweden) and the Swedish program for canister studies. This section included a cylindrical part (material code T31) and a cover lid (lock TX 82) welded together and marked KL 059 on the outer surface of the cover lid. Chemical analysis, short term mechanical properties and initial microstructures of the materials have been reported previously in [2]. In addition, a batch of low-phosphorus copper (Cu-OF) was added to the testing program to explore the effect of composition (phosphorus) on ductility and creep cracking. The OFP test materials (Fig. 1) were subjected to uniaxial and multiaxial (compact tension, CT) creep testing with and without a simulated Olkiluoto groundwater environment. The CT specimen notch for welded OFP copper applied the natural gap tip of the joint, while the notch for (parent) Cu-OF material used an EDM notch with a tip width of 0.3 mm. For testing CT specimens of OFP copper in aerated groundwater, a new testing facility was used with circulating medium at 90°C. Metallography using optical, scanning electron and FESEM/EBSD (Aalto University) microscopy has been applied for as-new materials and test specimens after testing periods. Interrupted testing has been applied for multiaxial testing to inspect for damage evolution. For load setting and interpretation of the results, life modelling with extended parametric and other techniques has been applied, including finite element (FE) analysis for the CT specimens [2-4].

For creep modelling, the combined Wilshire and LCSP models have been applied and further developed [5-9] to support robust FE analyses under non-homogenous stress and strain fields.



a) b)

Fig 1. Extraction (Cu-OFP) of a) uniaxial and b) CT specimens for testing

3 Results

3.1 Uniaxial testing

The planned uniaxial creep testing program of OFP copper has been completed, except for the specimen V1 (150°C/120 MPa) that has reached 75134 h (8.5 years) of testing time and a true strain well beyond 10%. At 63760 h the test was interrupted for visual inspection and physical measurements. At that point small surface cracks were observed. The diameter of the specimen was measured along the gauge length. It was found out that the elongation had still been rather uniform as the necking process had not yet started. The observed surface cracks were not located in the region of the smallest diameter, see Fig. 2. After inspection, the test was continued at the same loading conditions as before. When the test was again interrupted at 75134 h the previously detected surface cracks had not grown, but many more similar cracks had appeared (Fig. 3). The diameter had decreased during the second test period and the location of the smallest diameter had moved towards the location of the surface cracks observed at 63760 h, but no real necking has started yet.

The test K3 at 200°C/70 MPa is running at 21800 h. All testing results have been used to support creep modelling and to set the initial loading levels in multiaxial (CT) testing.

A new "impression creep" test facility has recently been acquired and is being tested for creep testing under compression. The small indenter is compressed against the test material at a constant load and the impression depth is continuously measured with an extensometer during the test. On the basis of the measured displacement rate the corresponding uniaxial creep rate can then be calculated. This test allows very local material zones to be measured, like these in weldments. For the welded copper the root area can now be separately tested as well as the fusion line or the areas with strings of oxide.

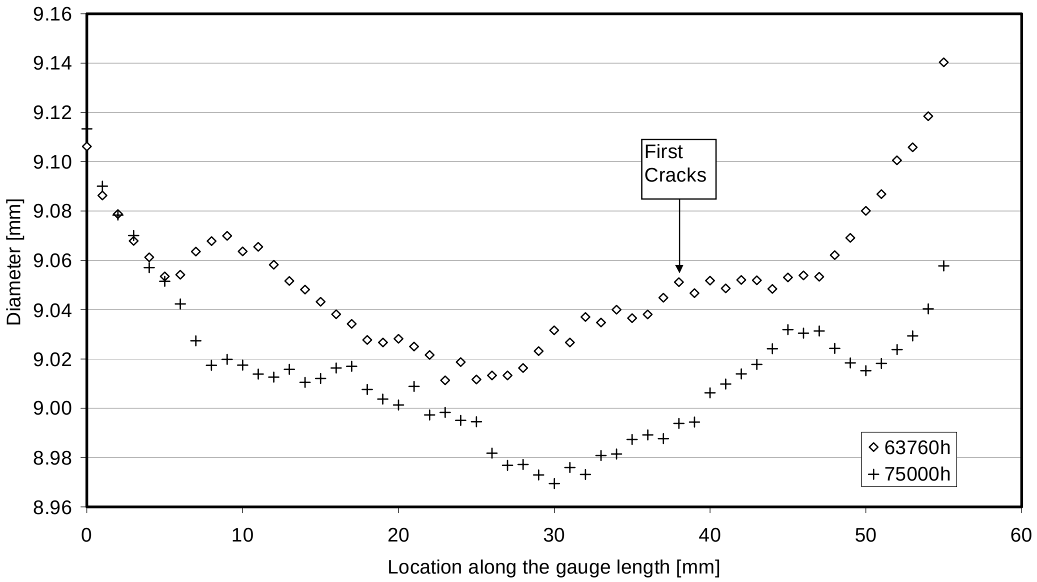


Fig. 2. Diameter variation along the gauge length of the uniaxial specimen V1 after 63760 and 75134 h at 150℃.

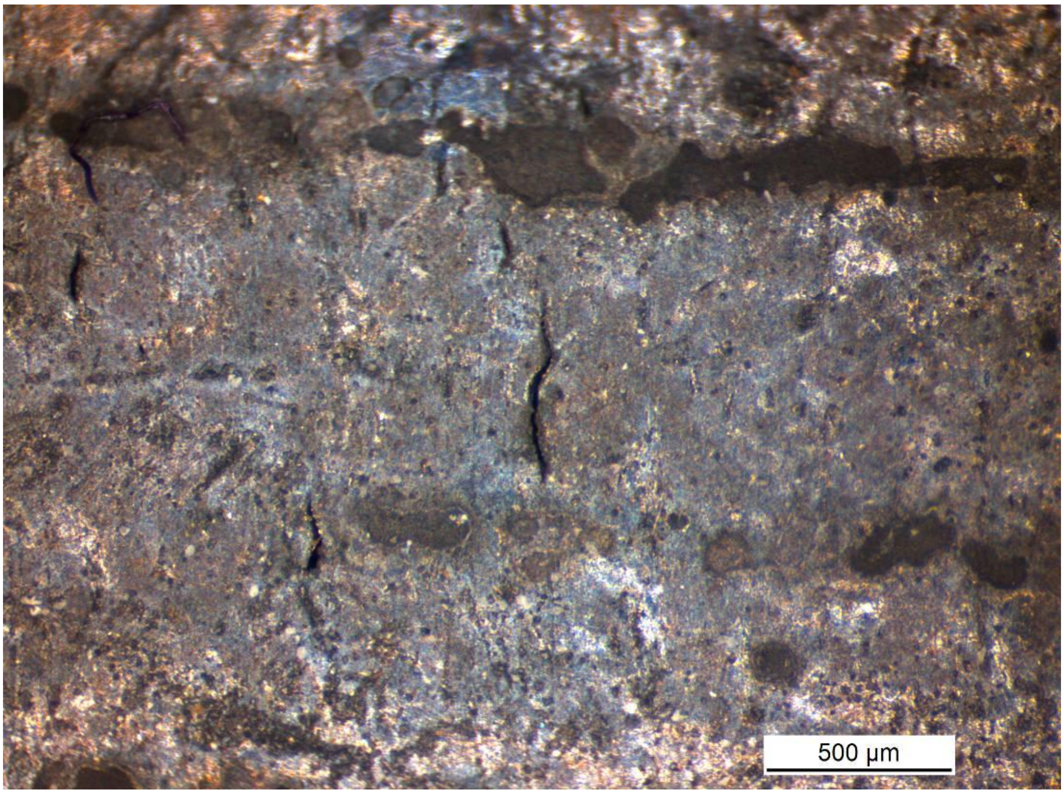


Fig. 3. New surface cracks in the uniaxial specimen V1 after 75134 h at 150℃.

3.2 Multiaxial testing

CT creep testing

The specimen CS3 (OFP copper) with a FSW joint was initially loaded at a (plane stress) Mises equivalent stress of 35 MPa, resulting in front face displacement (FFD) of 0.15 mm after the first testing cycle at 175°C. After each of the six testing cycles (5000 h each, up to 30000 h) the test was interrupted for microstructural and damage examination of the tip region. Early initiation of grain boundary separation (grain boundary cracking) was observed at the tip region after 25000 h.

The CT specimen is shown in Fig 4. After 25000 h of exposure the joint tip has opened about 0.13 mm, indicating local deformation at the notch tip, see Fig. 5. After 15000 h of exposure, the joint faces (“crack mouth”) had opened by about 0.03 mm for near zero crack growth. Although the opening was measured at a different location it is obvious that the opening process is now accelerating.

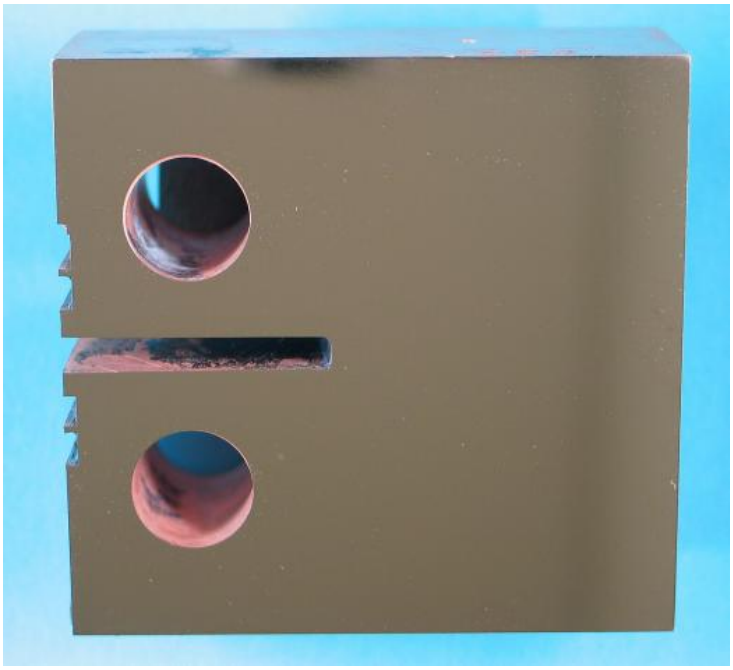


Fig 4. CT-specimen (CS3, OFP) after the first test cycle (175°C / 35 MPa)

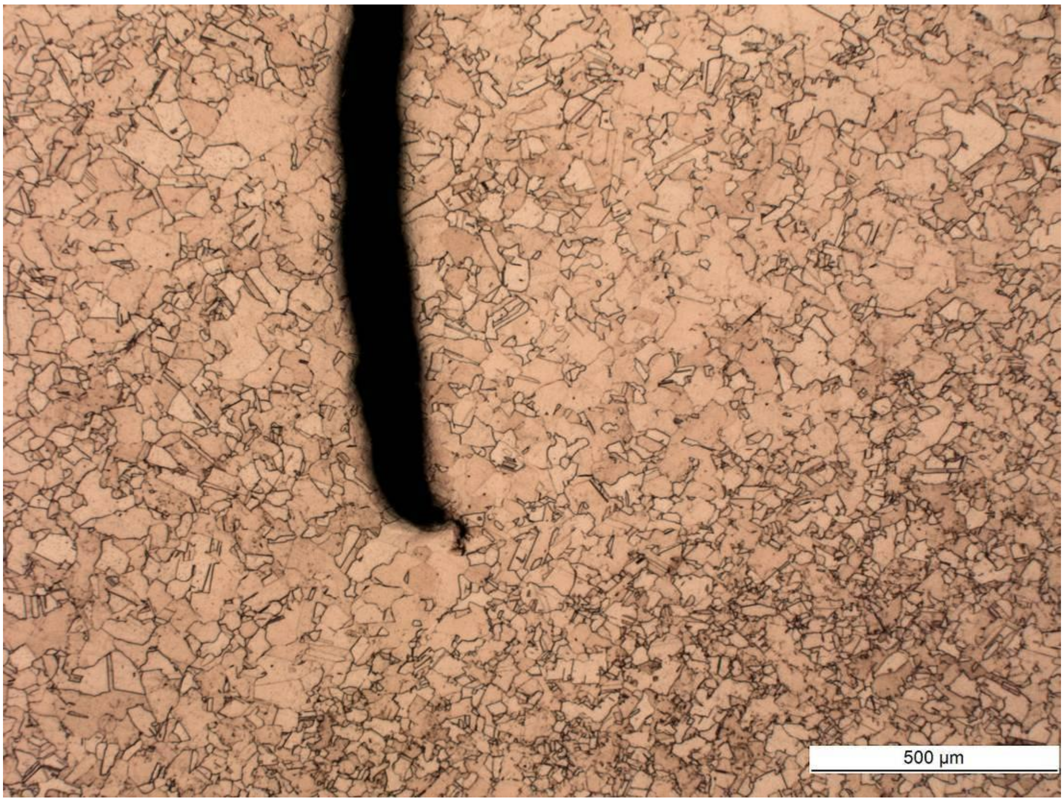


Fig 5. FSW joint tip and the FSW/BM borderline in specimen CS3 after 25000 h (175°C) of testing

Parallel CT testing with similarly sized Cu-OFHC base material specimens at 175°C was initiated so that the initial mouth opening was comparable to that in the tested Cu-OFP specimens. This was done to compensate for the lower creep strength level of Cu-OFHC. Nevertheless, in the first test a crack with brittle appearance started to grow relatively fast in less than 1000 h at K_I = 9 MPa√m. Intergranular cracking to about 8 mm required a notch mouth opening of only about 0.1 mm, reflecting low ductility. In CT tests at K_I = 8.25 MPa√m and K_I = 7.75 MPa√m at 175°C, cracking with brittle appearance and crack branching was observed after about 6200 h and 8334 h of testing respectively, see Figs. 15 and 16. A fourth test at 6 MPa√m is running at 10800 h and the test is expected to last about 20000 h in total.

3.3 Combined creep and corrosion (CT) testing

For combined creep and corrosion testing, the testing facility consists of a loading frame built into a constant load creep testing machine, with the specimen grips and the CT specimen designed to allow for continuous monitoring of the load line opening. The specimen is inserted to a glass jar where the simulated Olkiluoto groundwater (aerated) is circulated at a temperature of 90°C.

The test facility has been designed to minimise evaporation which is compensated for by adding distilled water. The conductivity of the test medium is monitored by intermittent sampling to control and maintain the salt concentration.

The second combined corrosion and creep test with welded CT specimens in the aerated transient conditions has been completed and the specimen has been inspected. In the first test of 227 h only local pitting corrosion was observed. After the second test of 1907 h grain boundary corrosion (intergranular attack) was observed on both side faces of the specimen mainly in the middle of the notch, see Figs 6-7. As there was less corrosion towards the joint tip, and no evidence of stress corrosion at the joint tip, testing was continued under same conditions. After a total (combined) testing time of 4400 h, heavy general corrosion to a maximum depth of about 2 mm was observed, Fig. 8.

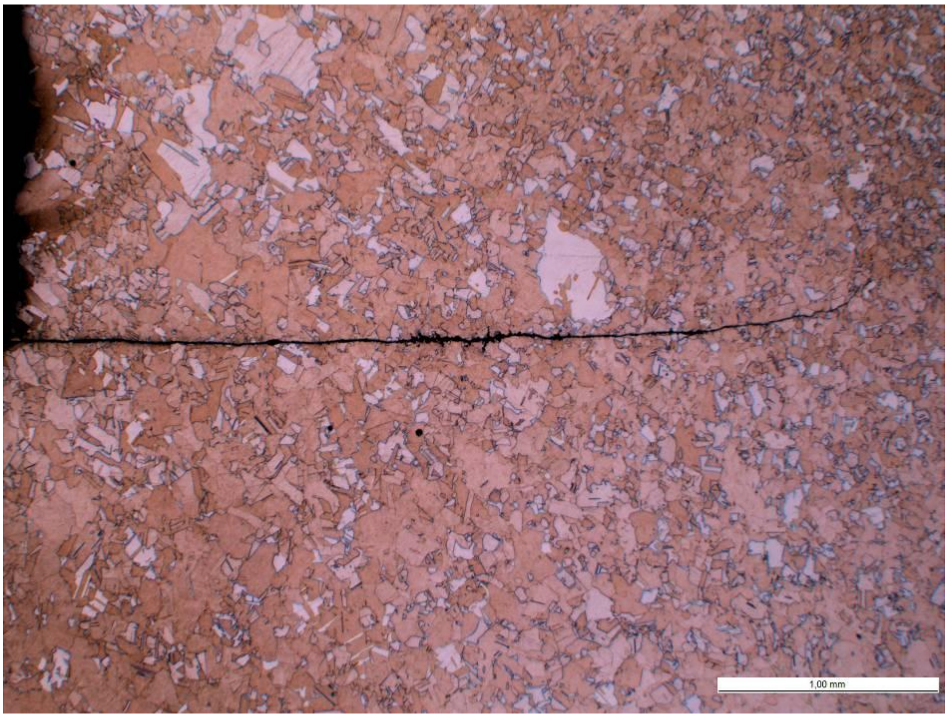


Fig. 6. The natural defect in specimen CS1 after 1907 h of testing in salt water at 90°C.

Also, even the glass test vessel was visibly corroded. It was first suspected that corrosion could be at least partly due to an electrochemical coupling between the sample and the titanium loading pins, possibly assisted by crevice corrosion in the gap between the specimen and the grips. However, the loss of material was mostly occurring on the front and side surfaces of the specimen and not in the holes for loading pins. Therefore, it appears more likely that general corrosion in aerated water with high salt content is to blame. Nevertheless, the loading pin material was changed to zirconium and the glass vessel was replaced by a teflon vessel for further tests of welded specimens. Future testing is recommended to be continued under anoxic conditions.

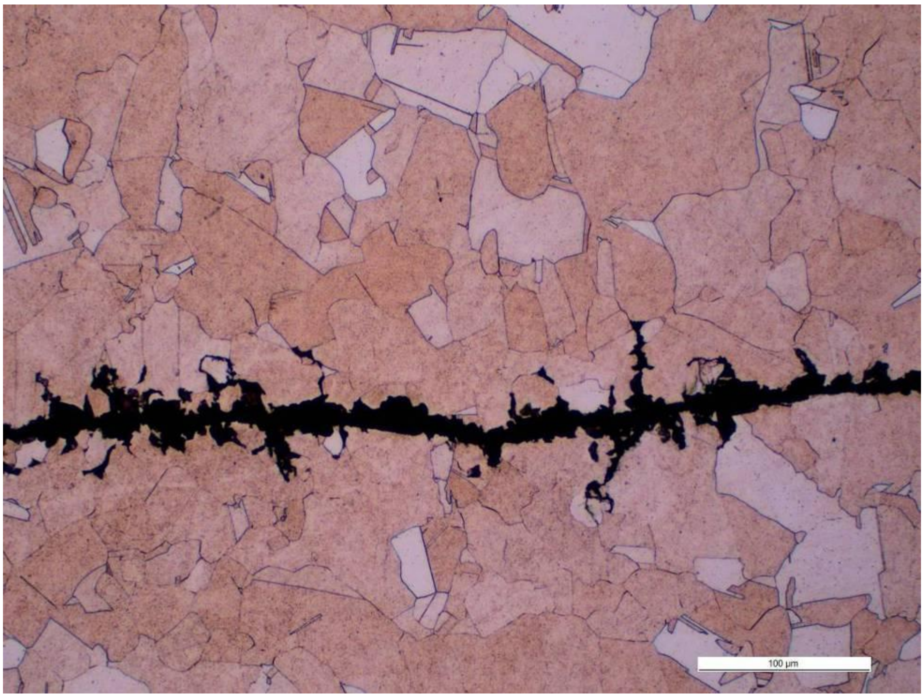


Fig. 7. A detail of Fig. 6 from the middle of the notch. Intergranular attack at the grain boundary.

Fig. 8. Extensive general corrosion in the CT specimen after 4400 h (90°C) in aerated simulated Olkiluoto groundwater

3.4 Metallography

CT: Cu-OFP

The OFP copper CT-specimen (CS-3) with a friction stir weld, tested at 175°C/35 MPa with interruptions every 5000 h, was subjected to optical and scanning electron (EBSD) microscopy after 25000 (Figs 9-13) and 30000 h of testing (Fig 14). Regarding the microstructural evolution in general, the earlier conclusion [3] was that the grain boundary zones at loaded grain boundaries grow with increasing time, temperature and stress (strain). In the inspection after 25000 h the width and amount of these zones appeared to have increased from the earlier levels. The nature of these grain boundary zones which appear like ridges in Fig 9 needs further quantifying investigation.

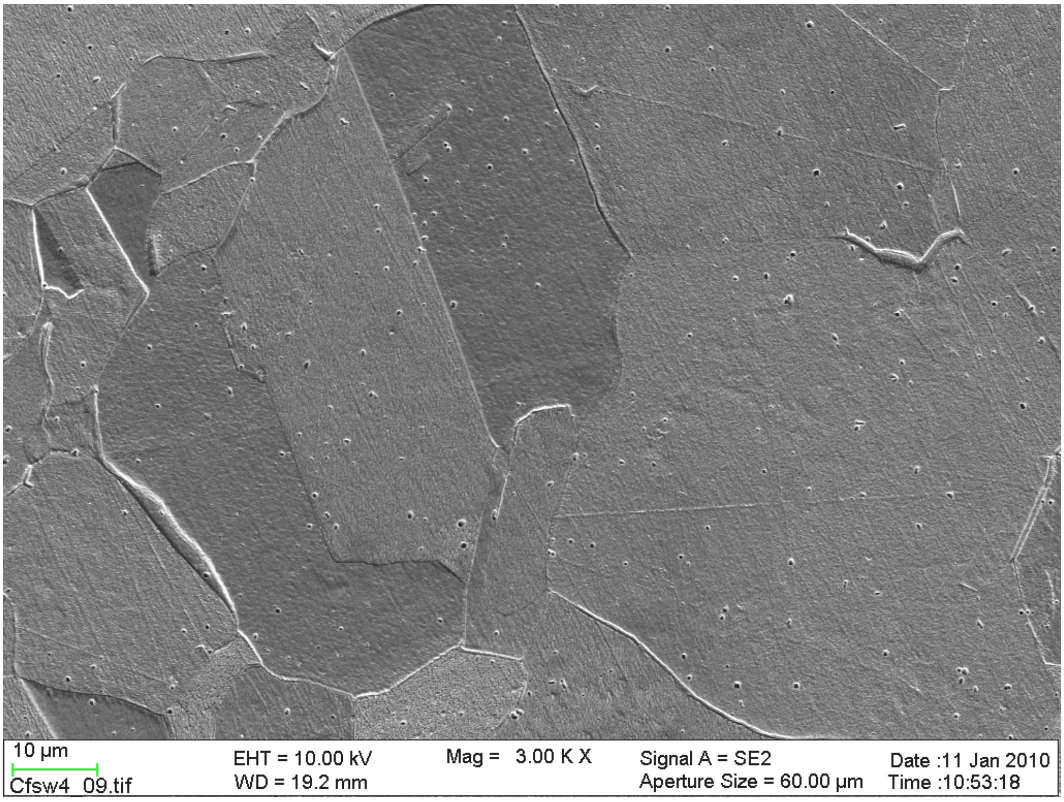


Fig. 9. Grain boundary widening zone near the joint tip in the specimen CS3 after 25000 h of testing (scanning electron micrograph)

With sufficient strain like in some of the longer term uniaxial tests, the grain boundaries will become decorated by a large number of small grains, i.e. the process results in recrystallisation [3,4]. No formation of the recovery zones has been observed within regions of lower stress/strain, such as outside the tip region of the CT specimens. The boundary between the friction stir weld and base metal at the joint tip can be seen in Fig. 10 as an EBSD grain orientation map after 25000 h. Strain localization as the distribution of small angle boundaries in the weld zone is shown in Fig. 11. Grain boundary cavities near the notch tip are shown in Fig 12, and the corresponding local misorientation map shows that the cavities are not associated with strong local deformation (Fig 13). The location of

Figs. 12-13 is shown in Fig 10. The microstructural features in OFP copper have been further elucidated in [10].

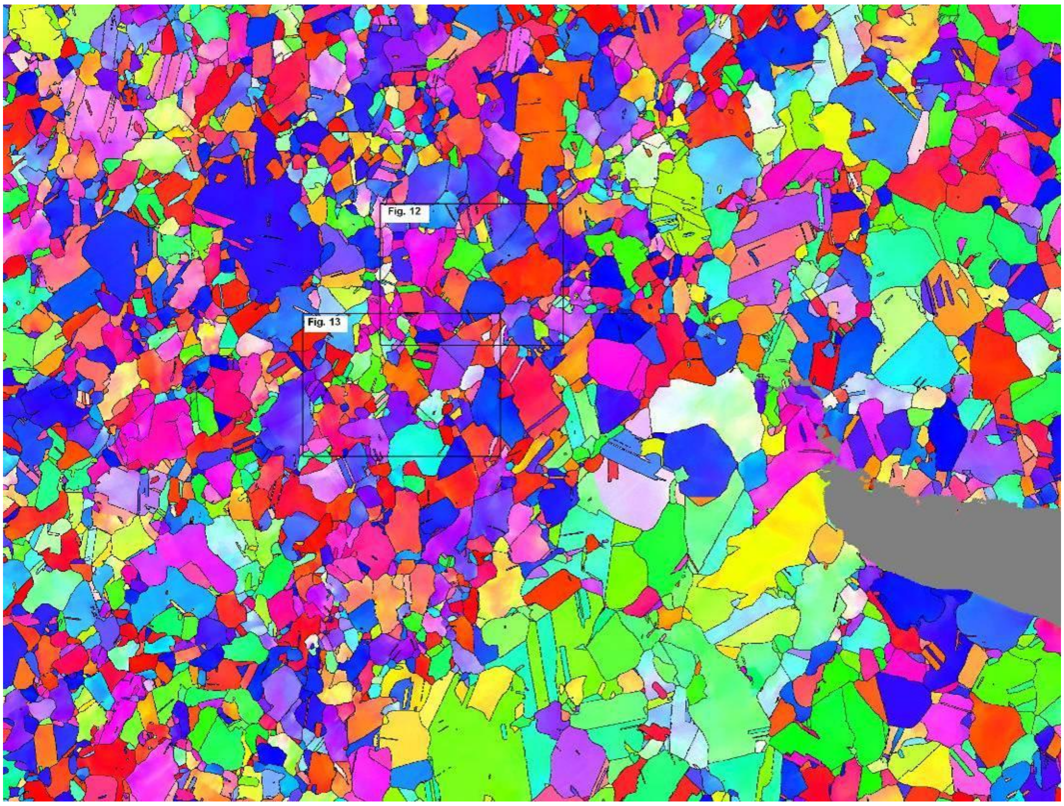


Fig. 10. EBSD grain orientation map IPF-Z, with locations of Figs 12-13 shown; the total width of the image is 1.07 mm; crack tip region is shown in light grey.

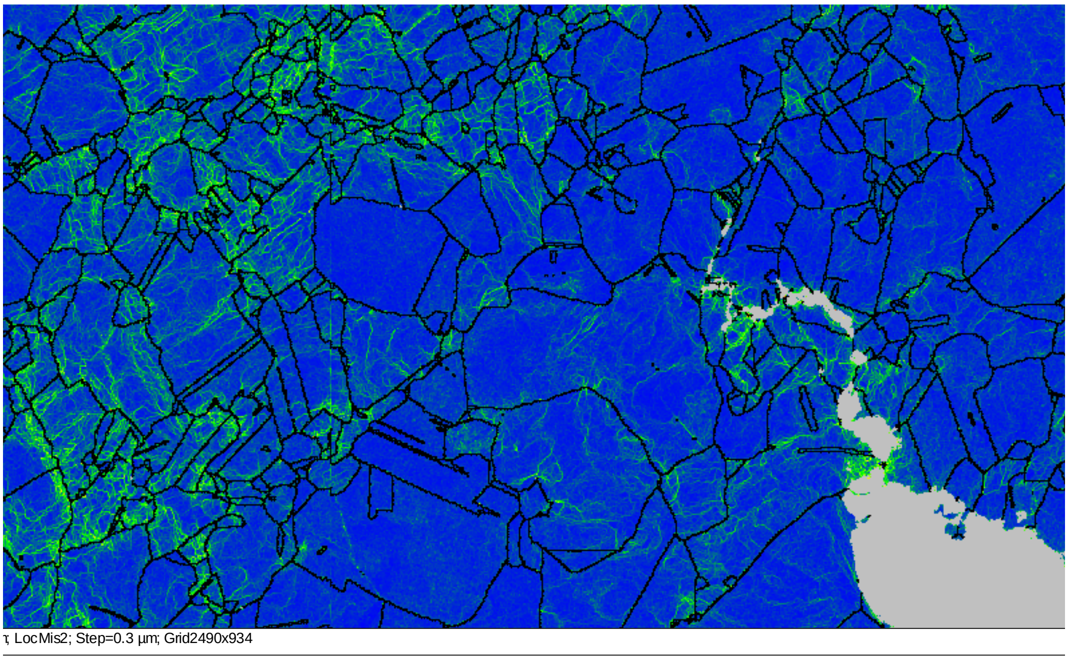


Fig 11. Local misorientation map at the FSW/BM interface (after 25000 h, main joint plane horizontal);small angle boundaries are shown in green; image width is 470 µm.

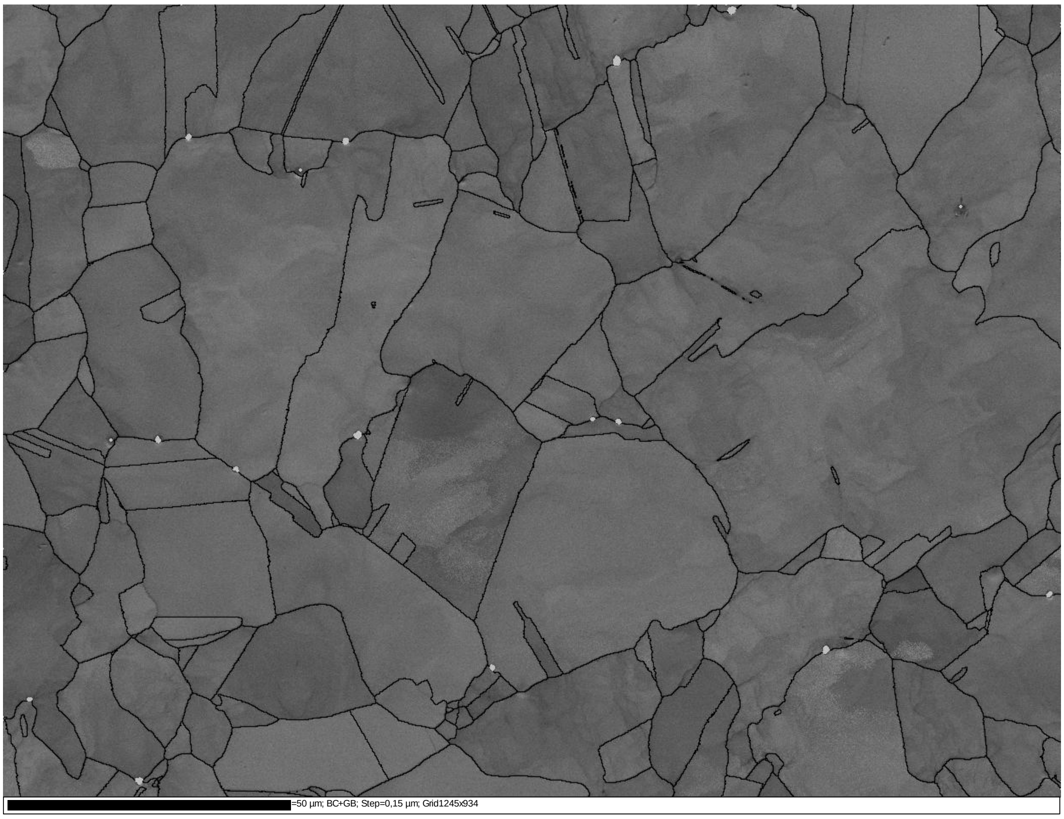


Fig 12. Grain boundary cavities near the crack tip of the CT specimen after 25000 h of testing (stir region); scale bar 50 µm; location indicated in Fig. 10.

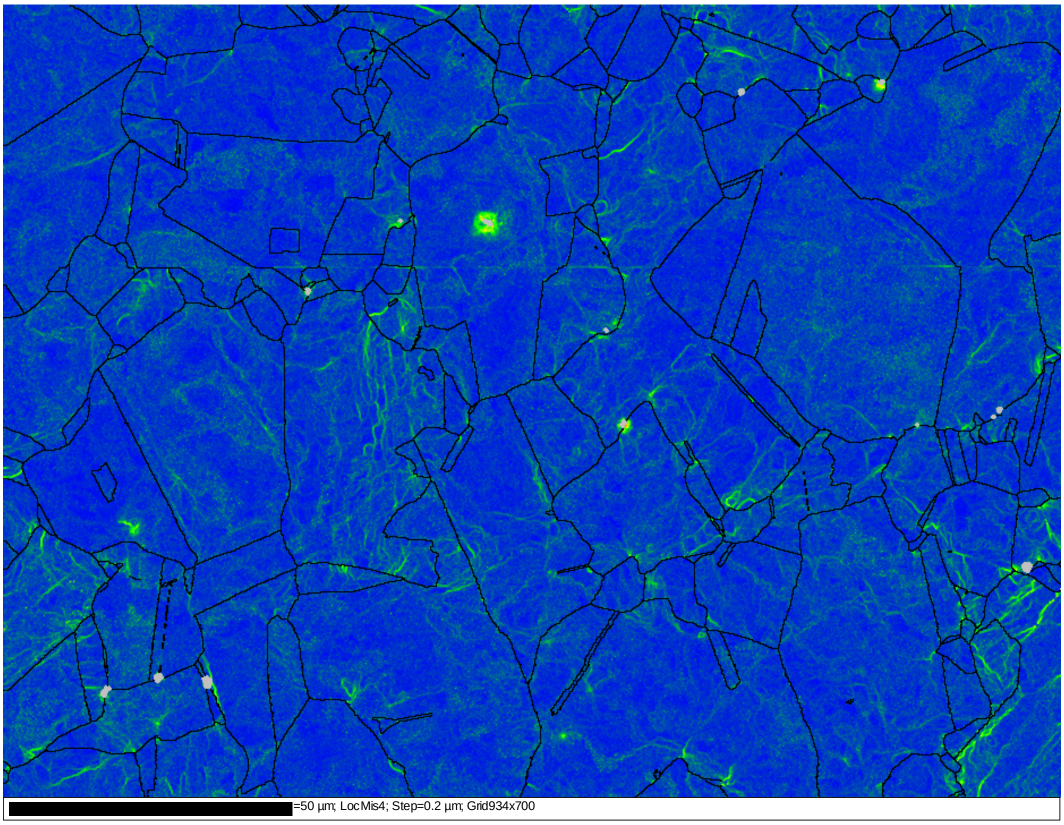


Fig 13. EBSD local misorientation map after 25000 h. Scale 50 µm. The location is indicated in Fig. 10.

The cavity density, as evaluated at the time of interrupted testing of the CT specimen, is shown as a function of time in Fig. 14. At the time of the first three interruptions the cavity density was below the limit of detection. After 15 000 h of testing the cavity density has clearly increased but has not resulted in any observed cavity coalescence or clear orientated formation up to 30 000 h.

As can be expected, the cavity density was found to increase towards the notch tip. After 25000 h the cavity density decreased quickly beyond a distance of 0.75 mm from the notch tip. In re-inspection after 30000 h of total testing time, the cavity density had further increased (Fig. 14), and cavities were associated with minimal deformation in the matrix. The area with observed cavities extended to some 1.2 mm ahead of the crack tip.

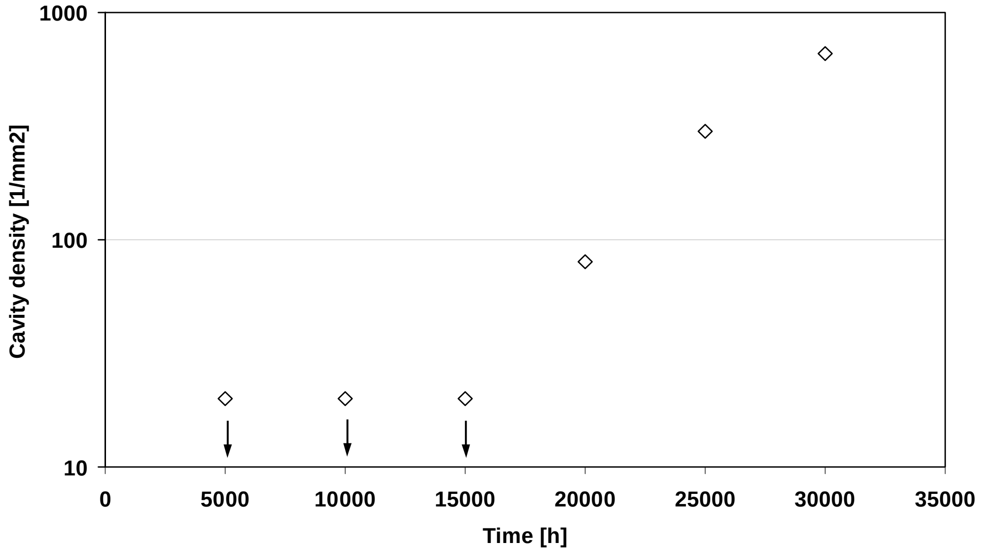


Fig 14. Cavity density in the OFP copper CT-specimen CS-3 with friction stir weld at 175°C/35 MPa reference stress; up to 15000 h the cavity size was below the limit of detection.

CT: Cu-OFHC

The first CT specimen of pure (OFHC) copper tested at K_I = 9 MPa√m and 175°C (base metal) showed already after 1000 h creep cavitation, crack initiation and growth on grain boundaries with brittle appearance, i.e. grain boundary damage at low overall deformation (strain). The second CT-specimen test at K_I = 8.25 MPa√m also showed brittle type of creep crack initiation and early growth after 6200 h. The third test at K_I = 7.75 MPa√m showed after 8334 h also crack growth with low ductility and pronounced crack branching as shown in Fig. 15, with an almost identical appearance with the previous test. Metallographic examination (Fig. 16) confirmed that the brittle intergranular cracking mechanism was by initiation, growth and coalescence of grain boundary cavities. Also, twinning deformation is seen in Fig. 16. A fourth test at K_I =6 MPa√m is running at 10800 h.

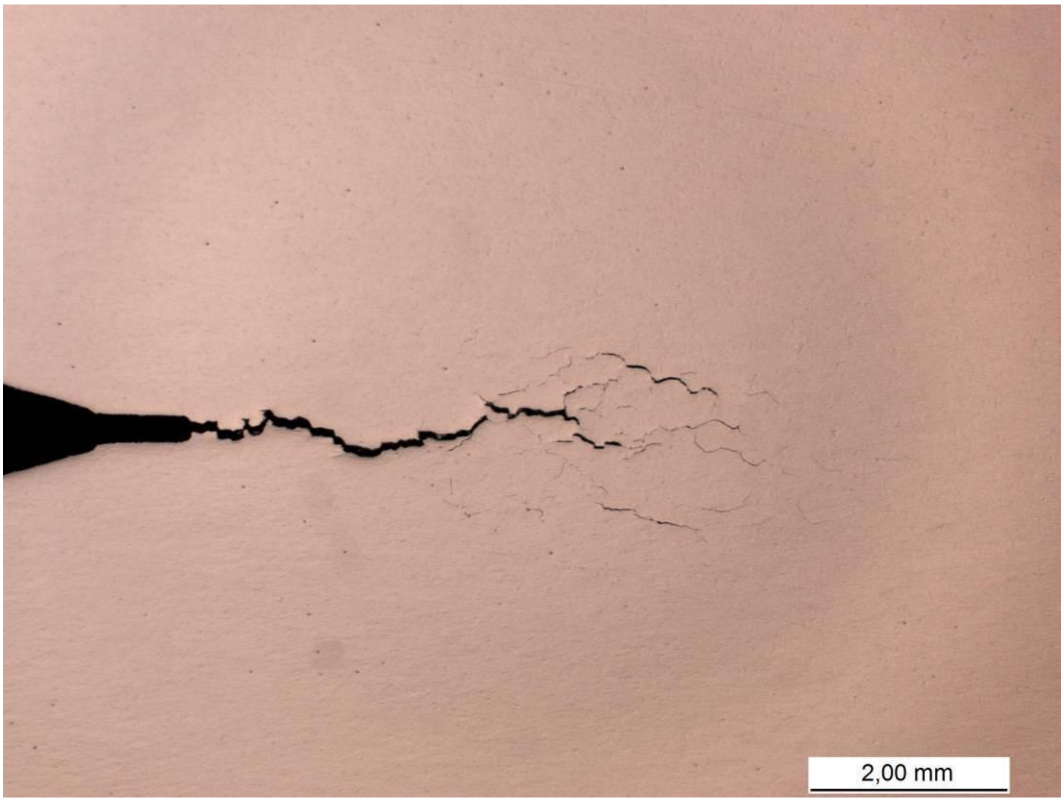


Fig 15. Crack branching in a Cu-OFHC (CT) specimen after 8334 h of testing

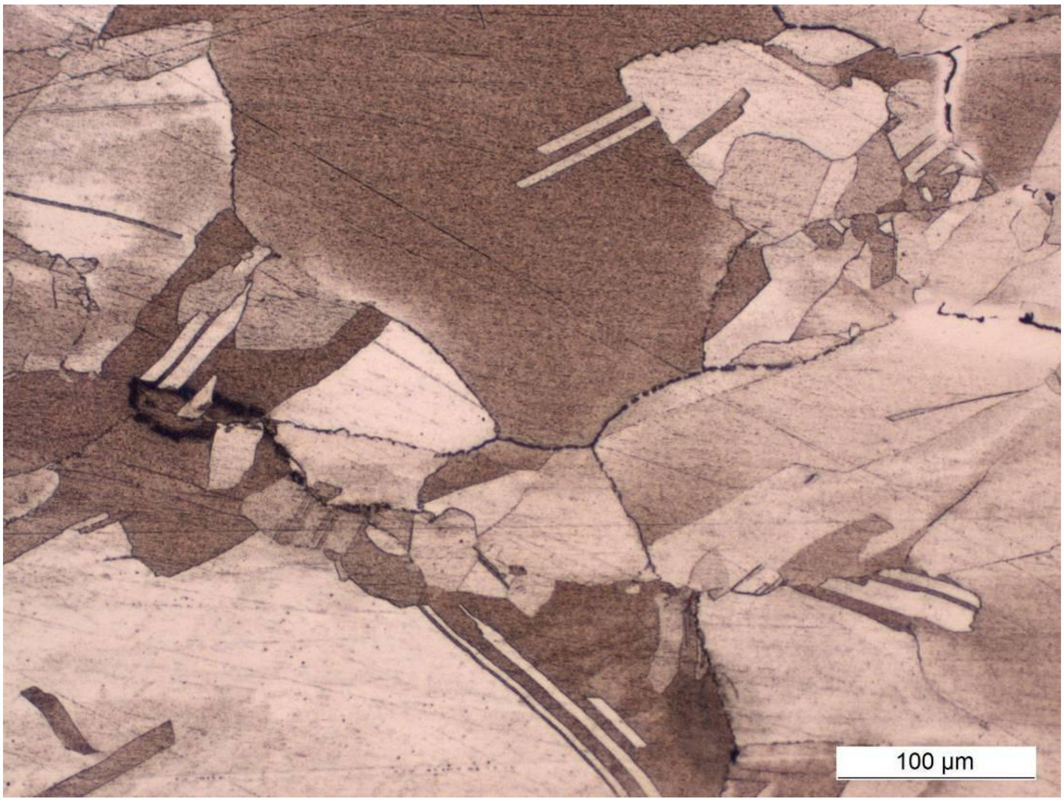


Fig 16. A detail of the grain boundary cracking in the specimen of Fig. 15

3.5 Creep modelling

The LCSP creep model [11] developed at VTT has been implemented and applied in FE analysis. Primary, secondary and tertiary creep terms are included in the model and analysis. In Fig. 17 the strain distribution of a CT specimen is shown. The analysis has been extended to characterise the state of multiaxiality at the crack tip in order to apply the LICON methodology to life prediction. The distribution of the multiaxiality parameter H (= max. principle stress / von Mises equivalent stress) ahead of the notch tip of a CT specimen is shown in Fig. 18. The corresponding distribution based on the Norton law creep analysis has been calculated for comparison (not shown). The analysis of stresses ahead of the crack tip for OFHC copper shows a zone near the notch tip where the equivalent stresses at three reference stress levels appear to overlap (Fig. 19). This can be seen as analogous to the process zone in traditional elasto-plastic fracture mechanics. [12]

The FE LCSP implementation is based on a formulation utilizing the principle of J_2 incremental plasticity in describing viscoplastic flow. In the numerical implementation the strain rate provided by the LCSP model is subjected to a random walk-like routine to evaluate the consistency of the FE strain increment particularly in the presence of high strain rates, such as those found near crack tips. The analyses can be carried out either using a local or non-local form of the LCSP model, where in the latter case a spatial size dependency is introduced to the constitutive law field variables. Labour related to modification of the implementation or introduction of a completely new material is reduced by the introduction of a Python interface between the FE routine and software used for its derivation, eliminating the need for user interaction or re-coding the constitutive law itself.

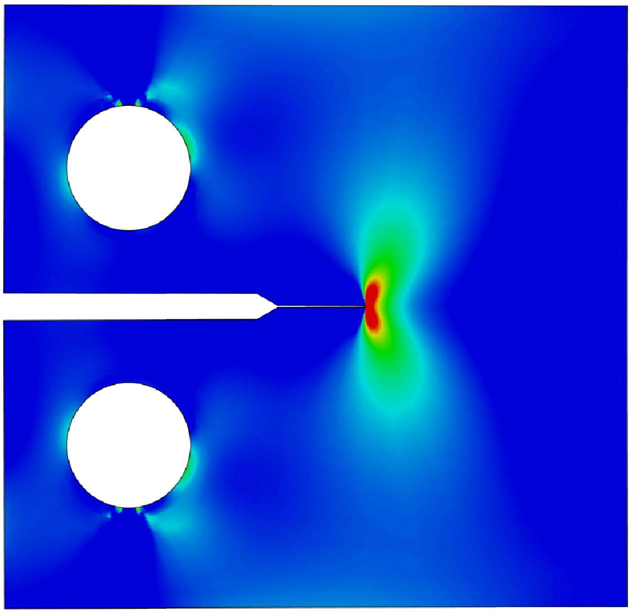


Fig. 17. Strain distribution of a CT specimen calculated using the LCSP creep model

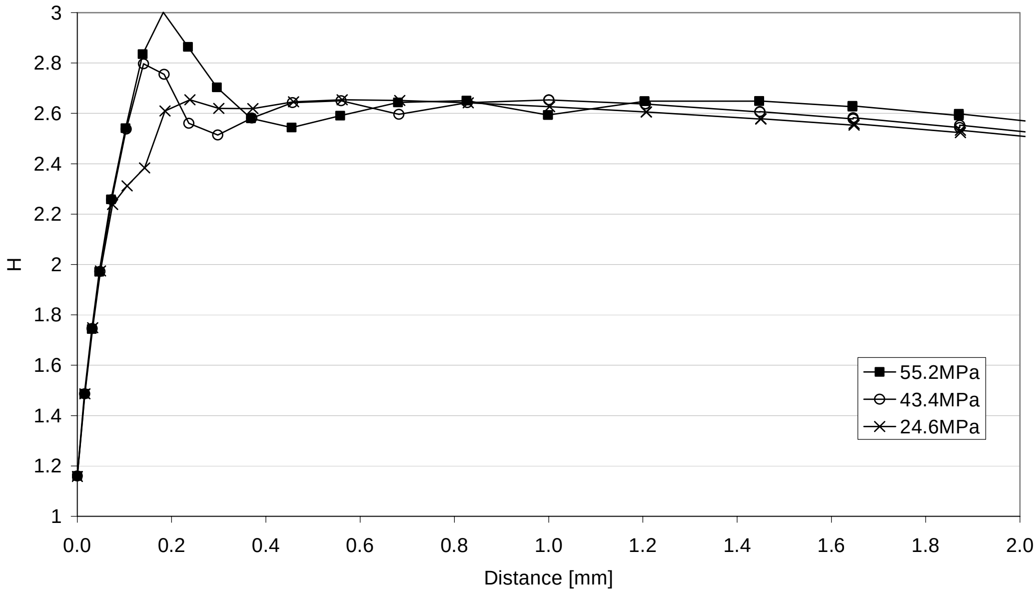


Fig. 18. Multiaxiality parameter H at the CT specimen notch tip at three reference stress levels calculated using the LCSP creep model for Cu-OFP

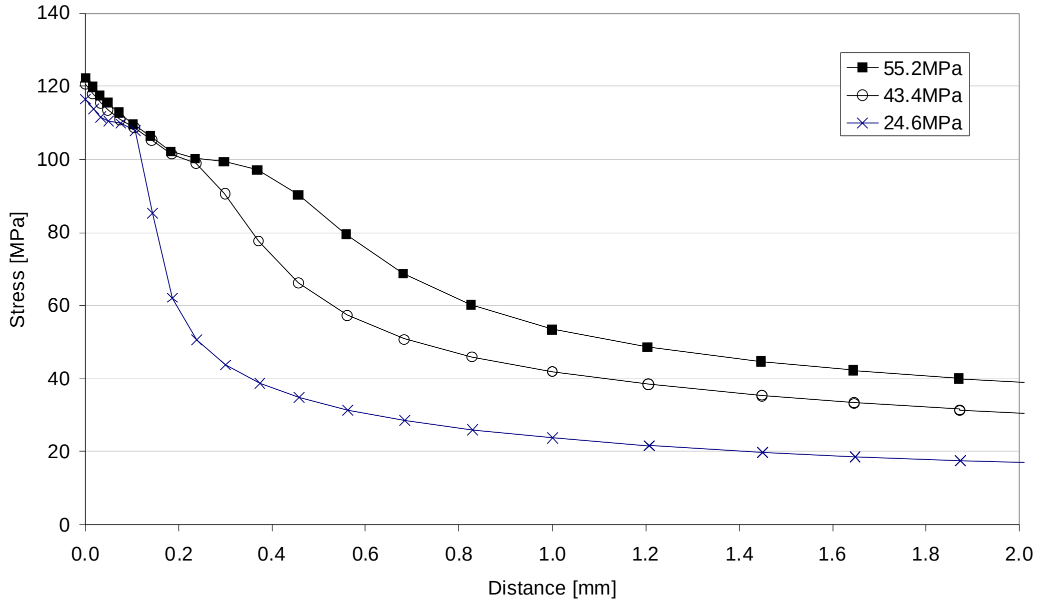


Fig. 19. Mises equivalent stress ahead of the CT specimen notch tip at three reference stress levels, calculated using the LCSP creep model for Cu-OFHC

3.6 Predicting time to rupture and strain

The capability of the LCSP model to predict well the strain rates [11] can be taken to suggest inversely a fair ability to predict time to rupture from relatively early strain data of unfailed specimens. Also, combining the LCSP with the Wilshire model (based on normalised stress) the long term predictions of both rupture and strain has been improved.

The Wilshire equation for time to rupture t_r (in seconds) at stress σ (MPa) and temperature T (K) is expressed as

$$\ln(\sigma / \sigma_{TS}) = -k[t_r \exp(-Q_c^* / RT)]^u \qquad (1)$$

where *k* and *u* are constants obtained by fitting to the test data, Q_c* is the apparent activation energy and σ_{TS} is tensile strength or another reference stress (like yield stress) at the specified temperature. The application of this model obviously requires data from both creep rupture testing and hot tensile testing. The base material constants for OFP and OFHC are presented in Table 1. It is to be noted that the predictions are sensitive to the optimized apparent activation energy and that the values applied in this work are the ones giving the optimal fit for the available data. For both OFP and OFHC copper somewhat larger Q_c* have been presented in earlier work [11, 13].

Table 1. Wilshire equation parameters for time to rupture of base material OFP and OFHC copper

Parameter	Value
OFP apparent activation energy, $Q^*_{c\text{-ref}}$	89 200 J/mole
k_{ref}	1.6288
u_{ref}	0.297
$\sigma_{TS\text{-ref}}[T(°C)]$	216-0.339·T(°C) MPa
OFHC apparent activation energy, $Q^*_{c\text{-ref}}$	61 400 J/mole
k_{ref}	1.2298
u_{ref}	0.166
$\sigma_{TS\text{-ref}}[T(K)]$	$191.31+0.65634\cdot T(K)-0.00185\cdot T(K)^2+0.0000010185\cdot T(K)^3$ MPa

The results of the life predictions are shown in Figs. 20-21. It is to be stressed that so far the OFHC data is a limited data set. The rupture life models are updated when more data is available.

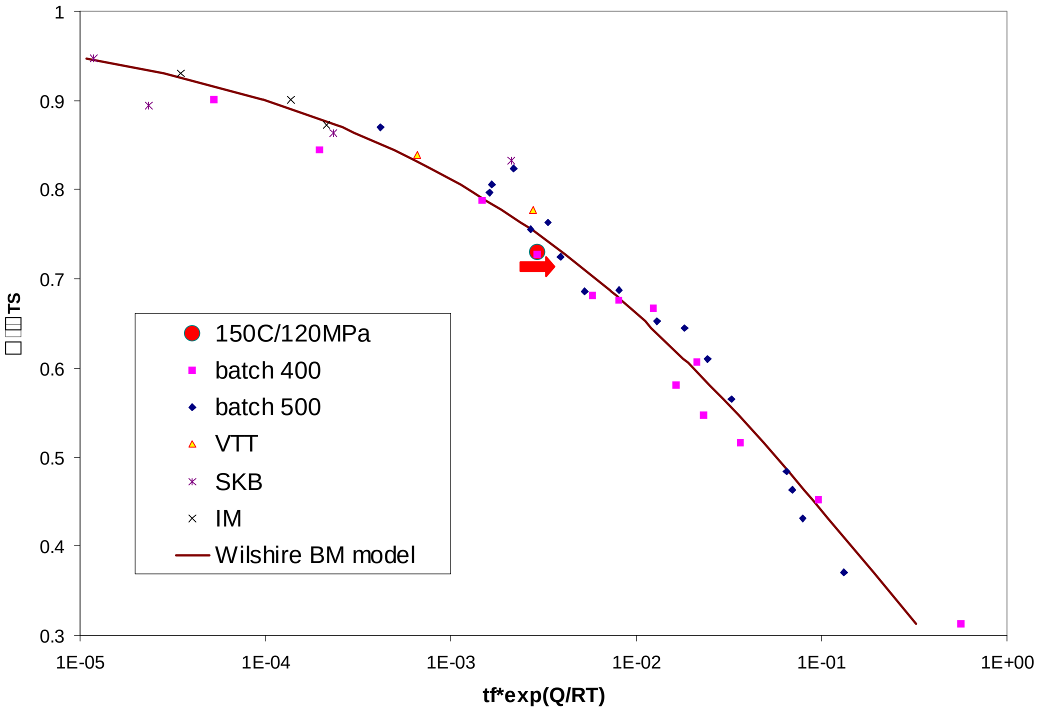


Fig 20. Wilshire model based life predictions for base material (BM) of OFP copper; the large red dot is the running 150℃/120 MPa uniaxial test (8.5 years, predicted life 12 years)

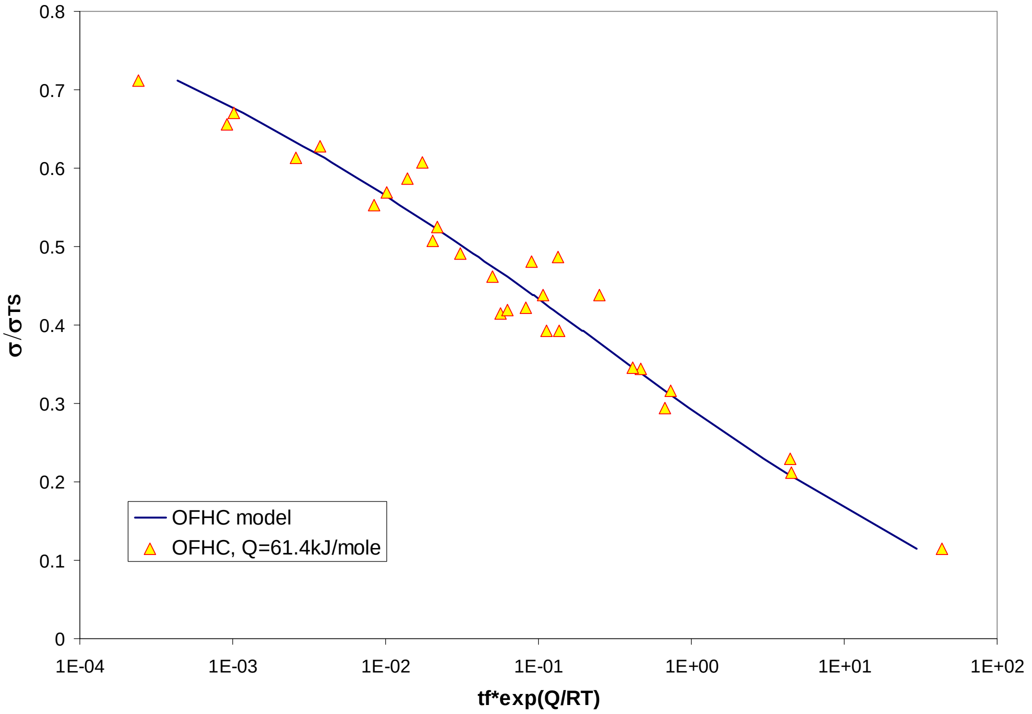


Fig 21. Wilshire model fit to creep rupture data [13] of OFHC copper

The strain and strain rate dependence of stress, temperature and time can be described by the LCSP functions:

$$\log(t_\varepsilon) = \frac{\log(t_r)+C}{1+\left(\dfrac{\log(\varepsilon)}{x_0}\right)^p} - C, \tag{2}$$

$$\log(\varepsilon_t) = \left(\frac{\log(t_r)+C}{\log(t_\varepsilon)+C} - 1\right)^{1/p} \cdot x_0, \tag{3}$$

$$\dot{\varepsilon} = -\varepsilon \cdot k_1 \cdot k_2 \cdot x_0, \tag{4}$$

where t_r is the time to rupture and x_0, p and C are fitting factors. In its simplest form the last three are constants but in most cases dependent on stress and temperature. The factors k_1 and k_2 are functions of time to strain. The model allows for convenient evaluation of minimum strain rates, and the predicted and measured minimum strain rates for the batches 400 and 500 of OFP copper in [14, 19] are presented in Fig. 22.

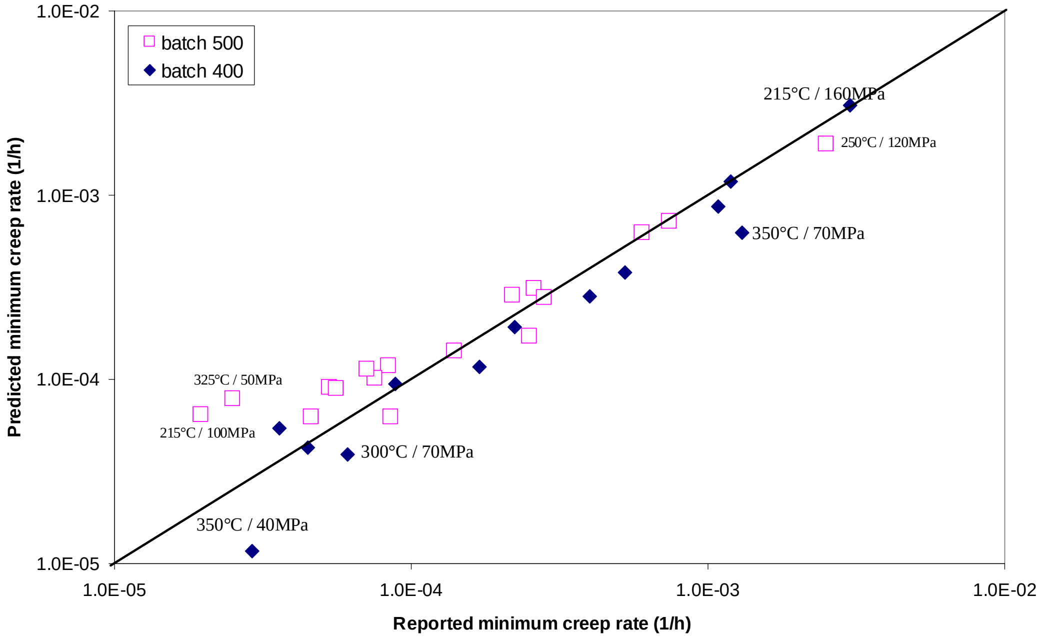


Fig 22. LCSP predicted OFP copper minimum strain rates against the measured ones for batch 400 and 500 in [14]. The line represents perfect fit.

The LCSP model can be considered as an equally suitable but simpler than the classical θ-model [15]. The combination of the Wilshire rupture model and the LCSP strain and strain rate models appear to work well for accurate and robust prediction of long term creep response for both Cu-OFHC and Cu-OFP materials.

4 Creep life prediction at final disposal conditions

The expired life fraction has been assessed for an exposure of 100 000 years at various assumed constant stress levels without any stress reduction factors (for welds), using the Wilshire and LCSP creep models and a conservative (dry buffer + gap) approximation of the design report temperature history [20], simplified by using a step-wise approximation of it for calculation purposes as shown by the dashed line in Fig. 23. The possible life shortening effects caused by multiaxiality or weld defects have not been included in this analysis.

The consumed life fraction after each temperature step of Fig 23 has also been indicated for three stress levels in Fig. 23. The expired life fraction after 100 000 years at each stress level has been shown in Table 2, including the stress level of 143 MPa that would result in failure.

Table 2. *The calculated life fraction at assumed stress levels after 100 000 years*

Stress	Predicted life fraction
80 MPa	1.63 %
100 MPa	4.65 %
120 MPa	15.54 %
143 MPa	100 %

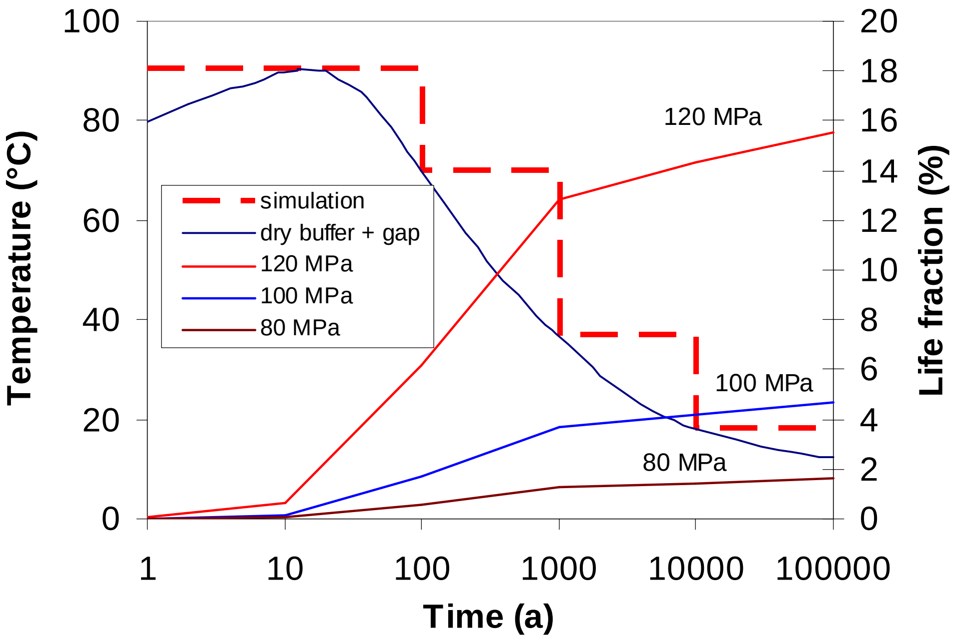


Fig 23. The updated temperature history of the copper canister [20] and the corresponding life fraction at three stress levels in final disposal conditions using the dry buffer assumption; red dashed line is a conservative estimate for temperature history used in life prediction

5 Implications related to the design analysis report

The SKB design analysis report [16] includes an assessment of the influence of creep of copper in the final disposal conditions. In particular, the creep life prediction in the design analysis report is largely based on test data accelerated by elevating stress rather than temperature. Unfortunately this approach can be considered non-conservative (predicting overly long life), and for this reason the opposite has been applied in the present work. For example, short term testing at low temperature and high stress (design analysis report p. 19) can explain why only notch strengthening is reported for creep of OFP copper. It is not clear that this should be the case in long term, since increasing notch weakening in time by natural tiny (FSW) weld defects has been found and reported at lower stress and modestly higher temperature [2, 8], and creep cavitation damage on grain boundaries under multiaxial (lower reference) stress has also been found as shown in the present report (Fig. 12).

The approach in the present project for assessing the long-term performance of copper under repository conditions is to keep the stresses close to the expected range of in-service stress levels and to increase the temperature to accelerate creep in laboratory conditions. This is to avoid non-conservative predicted life when extrapolating from the laboratory results to the actual conditions. The box in Fig. 24 indicates roughly the temperature and stress ranges of the mechanical testing data applied in the present project, to remain as close as possible to the temperature and stress ranges that the canister is expected to experience in service. As shown in Fig. 24, the deformation mechanism borderlines are not crossed when moving in the horizontal (temperature) direction in the deformation mechanism map. The type of damage observed in testing is therefore assumed to represent the damage occurring during service, as moving in the temperature direction in Fig. 24 does not involve mechanism changes and is only affecting the rates of damage development.

Furthermore, much of the earlier comparisons on predicted creep life were based on the assumption that the applied maximum stress levels could be small or moderate, of the order of 40-50 MPa. The background FE work referred to in the design analysis report (e.g. p. 62 in [16]) suggests that the local stress levels could be clearly higher. As this should have a significant impact on creep rates, the comparisons of life prediction with the applied material models should also be re-evaluated. Similarly, the maximum creep strains in the canister have been often predicted to remain small, typically of the order of few percent (even in case of rock shear, see p. 57 in [16]). Considering the FE results, larger local creep strains appear possible, perhaps even without (weld) defects or locally inhomogeneous material. Hence the potential effect of local strains appear underappreciated, considering the observed impact of defects, multiaxiality and notch weakening in shortening the creep life.

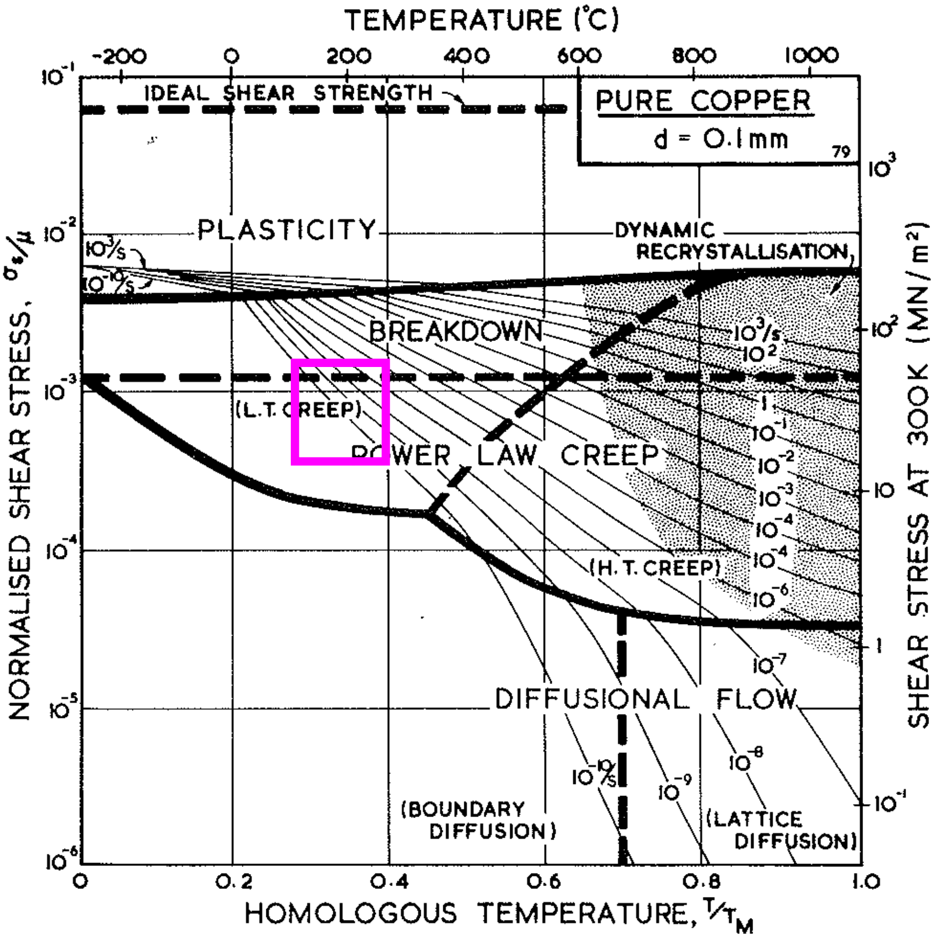


Fig 24. The deformation mechanism map [21] for pure copper, grain size 0.1 mm, with the conditions of VTT creep testing indicated.

It is suggested that some conclusions in [16] are doubtful and worth further study, for example the claimed universal notch strengthening and crack blunting in creep. Also, the report [16] finds no significant new or fast-acting threat by corrosion-related mechanisms to the copper overpack. While this may be justified for many tested environments, it may not hold under the reducing repository conditions according to recent observations of fast cracking damage even at room temperature [17, 18]. To test the potential effect in combination with creep (and the thermal dependence in general), reducing groundwater environment testing under stress and closer to the service temperature should be conducted.

In spite of what is stated above, it is still possible that the copper layer will perform in the repository in a satisfactory manner. However, it is not clear that this is completely justified as yet.

6 Publications

The following publications in 2010 have been issued in the project:

S Holmström. Engineering tools for robust creep modeling. Doctoral Dissertation, Aalto University. VTT Publication 728 (2010). VTT, Espoo, 94 + 53p.

J Rantala, P Auerkari, J Salonen, S Holmström, A Laukkanen, T Saukkonen. Mechanical performance and life prediction for canister copper, Baltica VIII, Int. Conf. on Life Management and Maintenance for Power Plants, Helsinki-Stockholm-Helsinki, May 18-20, 2010

In addition, a special session on canister issues including copper creep was organised in the Baltica VIII Conference on Life Management and Maintenance for Power Plants, Helsinki-Stockholm-Helsinki, May 18-20, 2010 (VTT Symposium 264, Vol 1, ISBN 978-951-38-77591-6)

7 Conclusions and summary

Changes in base material and FSW welds of OFP copper have been nvestigated after low temperature (150-175°C), low stress (35-120 MPa) creep experiments. The observed changes in the multiaxial (CT) specimens tested up to 30 000 h (3.4 years) at 175°C appear to be largely restricted to widening recovery zones at stressed grain boundaries and to increasing grain boundary cavitation that had first emerged after 15 000 h of testing at the natural (joint) notch tip. The cavitation damage appears to be related to the combined local strain and stress state in front of the notch/crack tip. The results from CT tests and earlier tests with nominally uniaxial but defective specimens [2, 3] suggest that multiaxiality is important in controlling and limiting creep life. In comparison, fast evolving intergranular creep damage, crack branching and low ductility was confirmed in pure (OFHC) copper in CT specimens tested up to 10 400 h (1.2 years), while much higher creep ductility has been retained in OFP copper so far.

The longest continuing uniaxial creep test (150°C/120 MPa) for OFP copper has exceeded 75 000 h (8.5 years). For damage modelling it is of interest that interrupted testing of the longest uniaxial specimen has also shown distributed microcracking. The observed [2] effect of small scale natural weld (FSW) defects suggests increasing notch weakening with increasing time to rupture (decreasing stress). The test results continue to support creep modelling and have been used for life assessment with the latest expected temperature history of the canister at different assumed stress levels, using a combined Wilshire and LCSP creep model for OFP copper. The resulting predicted allowable (constant) stress level for a lifetime of 100 000 years would be about 140 MPa for the copper overpack.

In the combined corrosion and creep testing with welded CT specimens immersed in aerated simulated Olkiluoto groundwater at 90°C, heavy general corrosion up to a depth of about 2 mm was observed already after 4400 h of testing. In comparison to this, no significant indications of localised corrosion have been observed. Further work is suggested to clarify the temperature dependence of reported stress corrosion under reducing groundwater conditions.

The results appear to carry important implications relevant for the final disposal conditions. The earlier assumption of low stress level in repository conditions may not hold as very high stresses are also foreseen by the design report [16] for the copper overpack even after long times. It is suggested that the vessel stress analysis is repeated using the VTT creep model for an independent verification of the stresses especially in the weld region.

It is also suggested that some conclusions of the design report [16] are worth further study including experimental confirmation, such as the claimed notch strengthening in creep that contradicts the observed life shortening reported in [2], and potentially non-conservative life assessment based on high stress-low temperature creep test results.

References

1. National research program on nuclear waste management, 2006-2010 (KYT2010), Framework program for the research period 2006-2010, 26.9.2005. KYT - management committee, Finland (in Finnish)
2. Auerkari P, Rantala J, Salonen J, Laukkanen A, Holmström S, Kinnunen T. Effect of defects on low temperature creep of OFP copper, 2nd Intl. ECCC Conference, Creep & Fracture in High Temperature Components – Design & Life Assessment, April 21-23, 2009, Dübendorf, Switzerland
3. Auerkari P, Rantala J, Salonen J, Holmström S, Saukkonen T, 2007. Long-term integrity of copper overpack - experiments. VTT Research Report VTT-R-02129-08, Espoo. 15 p.
4. J. Rantala, J. Salonen, P. Auerkari, S. Holmström, T. Saukkonen, Long-term integrity of copper overpack – Final report 2009, KYT 2006-2010
5. Holmström S, Auerkari P, 2008. Creep rupture and strain for OFP copper. VTT Research Report VTT-R-08621-07. Espoo, 13 p.
6. Auerkari P, Holmström S, Rantala J, Salonen J. Creep Damage Ductility and Expected Life for Materials with Defects, paper 61428 in Proc. of PVP 2008, ASME Pressure Vessels and Piping Conf., July 27-31, 2008, Chicago, Illinois, USA
7. Holmström S, Auerkari P. Predicting creep rupture from early strain data. International Conference of Creep (Creep 2008), Bayreuth 2008. Paper CP-035, 8 p.
8. Auerkari P, Holmström S, Rantala J, Salonen J. Creep Damage, Ductility and Expected Life for Materials with Defects, Proceedings of PVP 2008, ASME Pressure Vessels and Piping Conference, July 2731, Chicago, Illinois, USA
9. Wilshire B, Bache M B. Cost effective prediction of creep design data for power plant steels. 2nd Intl. ECCC Conference on Creep & Fracture in High Temperature Components – Design & Life Assessment. April 21-23, 2009, Dübendorf, Switzerland.
10. Saukkonen T, Savolainen K, Mononen J, Hänninen H. Microstructure and Texture Analysis of Friction Stir Welds of Copper. In Rollet AD (Editor) Materials Processing and Texture. Ceramic Transactions (Vol. 200). A Collection of Papers Presented at the 15th International Conference on Textures of Materials, 1-6 June 2008, Pittsburgh, Pennsylvania, John Wiley & Sons, pp 53-60. ISBN 978-0-470-40834-6
11. Holmström S. Engineering tools for robust creep modeling. Dissertation/VTT Publication 728 (2010). VTT, Espoo, 94 + 53 p.
12. Rantala J, Auerkari P, Salonen J, Holmström S, Laukkanen A, Saukkonen T. Mechanical performance and life prediction for canister copper, Baltica VIII, Intl Conf on Life Management and Maintenance for Power Plants, Helsinki-Stockholm-Helsinki, May 18-20, 2010
13. Wilshire B, Battenbough A J. Creep and creep fracture of polycrystalline copper. Materials Science and Engineering A, A 443 (2007). pp.156-166

14. Lindblom J, Henderson P, Seitisleam F. Creep testing of oxygen free phosphorus copper and extrapolation of the results. Swedish Institute for Metals Research, IM-3197, Feb. 1995.

15. Dutton R. A methodology to analyze the creep behaviour of nuclear fuel waste containers. AECL-11249, COG-95-06

16. Raiko H, Sandström R, Ryden H, Johansson M. Design analysis report for the canister. SKB Technical Report TR-10-28, April 2010. 80 p.

17. Arilahti, E., Lehtikuusi, T., Olin, M., Saario, T. and Varis, P., Sulphide induced stress corrosion cracking of CuOFP in groundwater. 4th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems. June 28 – July 2, 2010, Brugge, Belgium.

18. Arilahti, E., Lehtikuusi, T., Olin, M., Saario, T. and Varis, P., Evidence for internal diffusion of sulphide from groundwater into grain boundaries ahead of a crack tip in CuOFP copper, paper proposed for publication in Journal of Corrosion Technology, Science and Engineering, 2010.

19. Seitisleam F, Henderson P, Lindblom J. Creep of copper for nuclear waste containment – results of creep and tensile tests on Cu-OF, Cu-OFP, Cathode copper and welded joints. Swedish Institute for Metals Research, IM-3327, Feb. 1996.

20. Raiko, H. Structural Design of Disposal Canister, POSIVA report 2011-xx, To Be Published.

21. H.J. Frost and M.F. Ashby: Deformation-mechanism maps. The plasticity and Creep of Metals and Ceramics, Pergamon Press, 1982.