KYT 2014 / MICO

Material integrity of welded copper overpack – Final report 2012

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Confidentiality: Public

Report's title	
Material integrity of welded copper overpack – Final report 2012	
Customer, contact person, address	Order reference
KYT 2014	
Project name	Project number/Short name
MICO2012	73824
Authors	Pages
Juhani Rantala, Jorma Salonen, Pertti Auerkari, Anssi Laukkanen, Stefan Holmström / VTT; Tapio Saukkonen / Aalto University	30
Keywords	Report identification code
creep, corrosion, copper, repository, life	VTT-R-01515-13

Summary

Multiaxial loading of the CT specimens, tested up to 45 000 h at 175°C, continues to show damage evolution as grain boundary cavitation that is related to the local stress-strain state in front of the notch/crack tip.

In Cu-OFHC the intergranular creep damage was observed to evolve very fast, resulting in branched crack extension soon after loading and decreasing rate of damage due to decreasing effective stress intensity by branching.

The longest continuing uniaxial creep test (150°C/120 MPa) of OFP copper has exceeded a testing time of 91000 h (10.4 years). Inspection of the specimen suggests that in spite of considerable axial strain of more than 10% and persistent surface microcracking, the base material specimen shows no indication of approaching plastic instability or crack growth. The longest multiaxial (CT) test with a "natural" joint notch was also interrupted for inspection, and showed a rather steady maximum cavity density in the vicinity of the notch.

The material model (LCSP) was updated according to the test results and implemented to FEA code. The results of FEA suggest sustained concentration of tensile stress and strain close to the external (FSW) weld surface, with potential for locally concentrating damage. Otherwise, the predicted stress distributions differ markedly from those suggested previously elsewhere, and further work is suggested to clarify the discrepancy. In particular, the short and long-term relaxed stress levels are substantially lower than those previously predicted. It is essential to be able to model accurately the initial part of the loading response to successfully and accurately predict the long-term life.

Confidentiality	Public

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Distribution (customer and VTT)	
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Preface

This report provides the final annual report of the project "Material integrity of welded copper overpack" (MICO2012), including and summarising the experimental, modelling and life assessment activities as well as the results and status of the project up to end of 2012. One of the main achievements of the work is the new creep regime FE stress-strain analysis of the copper overpack. The parallel experimental work has provided the basis for the development of the LCSP creep model that has been utilised in the FE analysis. The project is a part of the Finnish national research program [1] on nuclear waste management, 2011-2014 (KYT2014) /1/. The financial support and other guidance by this program, STUK (Finland) and SSM (Sweden) are gratefully acknowledged.

Espoo, February 28, 2013

Authors

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1 Introduction

1.1 Background

In the repository for spent fuel, the temperature of the canister surface is expected to peak at about 75-90°C before the first hundred years /2/, with gradual cooling to the level of the bedrock environment (Fig 1). 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 technical challenge to life estimation for ensuring the integrity of the overpack. This is because of the discrepancy between the longest achievable laboratory test (less than decades) compared to the design life that is of the order of glaciation cycles (about 10^5 years) to reduce the radioactivity of the contents close to the background level. The time difference by a factor of about 10^4 also exceeds the usual range of extrapolation from laboratory experiments to real service conditions in most (or any) comparable engineering applications.
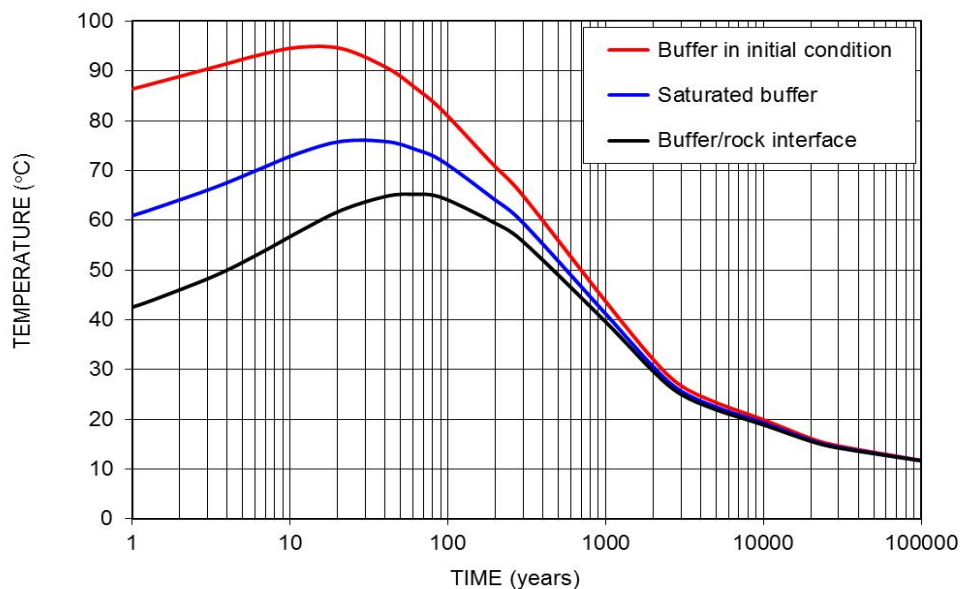

Fig 1. Predicted temperature evolution at the canister surface for EPR fuel /2/; the red curve assumes dry environment with a 10 mm gap around the canister.

This work will deal with both damage mechanisms to provide a realistic model for life prediction and long term behaviour of the copper overpack, including in particular

- assessment of damage mechanisms and their possible 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 2011-2014 (KYT2014). The project also includes specific issues defined by SSM (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 2012 have been:

- to update the creep model 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 including friction stir welded (FSW) material from a full scale section provided by SSM/SKI (Sweden) and the Swedish program for canister studies. The sample materials included a cylindrical part (material code T31) and a cover lid (lock TX 82) welded together, and a sector of a full FSW joint (L75). Chemical analysis, short term mechanical properties and initial microstructures of the materials have been reported previously [3]. In addition, a batch of low-phosphorus oxygen-free high conductivity copper (Cu-OFHC) was added to the testing program to explore the effect of composition (phosphorus) on ductility and creep cracking. The OFP test materials (Fig. 2) were subjected to uniaxial and multiaxial (compact tension, CT) creep testing with and without a simulated Olkiluoto groundwater environment. The diameter of the uniaxial specimens is 10 mm and the initial thickness (B) of each CT specimen is 25.00 mm. The notch of the OFP copper CT specimens with welds was the natural gap tip of the joint, while the notch for (parent) Cu-OFHC material was an EDM notch with a tip width of 0.3 mm. For testing CT specimens of OFP copper in aerated groundwater, a 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 each given testing period. 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 [3-5].

For creep modelling, the combined Wilshire and LCSP models have been applied and further developed [6-9] to support robust FE analyses under non-homogenous stress and strain fields.

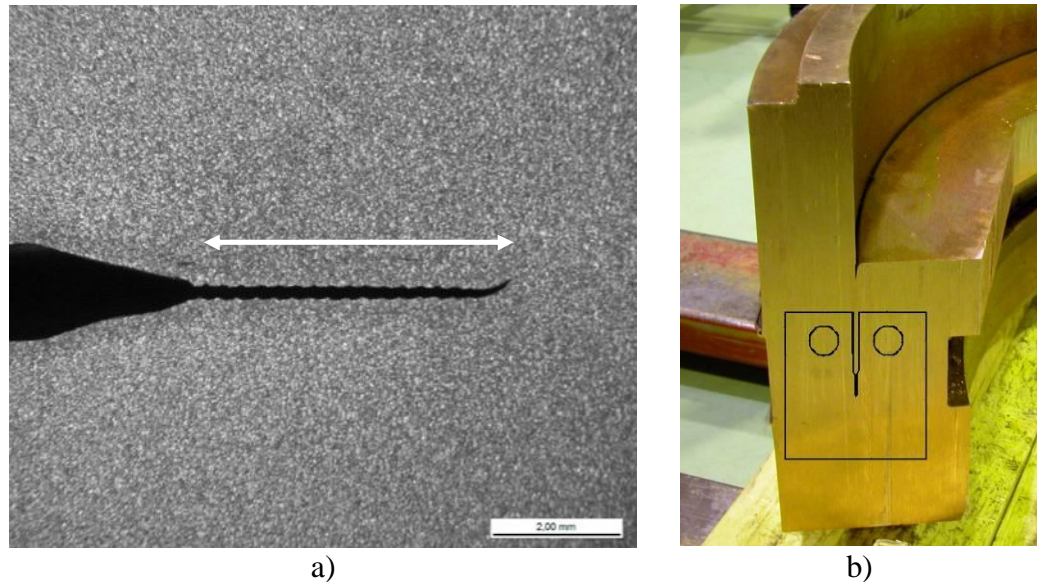a)   b)

Fig 2. a) EB-welded CT specimen after wire erosion (arrow shows the region of the natural joint gap) and b) extraction of FSW CT specimens for testing

3 Results

3.1 Uniaxial creep testing

The uniaxial creep testing program of OFP copper is on-going with two long-running tests. The specimen V1 (150°C/120 MPa) has reached 91 148 h (10.4 years) of testing time and a true strain of beyond 10%. The test has been interrupted three times for measurement of the gauge diameter and crack observation. At 63 760 h small surface cracks were observed and these cracks have remained practically unchanged during the following inspections at 75 134 and 91 148 h, see Fig. 3. Measuring the specimen diameter shows rather uniform reduction of gauge diameter over the whole gauge length without very localised necking, see Fig. 4.

The test K3 at 200°C/70 MPa is running at 41 500 h. All testing results have been used to support creep modelling and to set the initial loading levels in multiaxial (CT) testing.

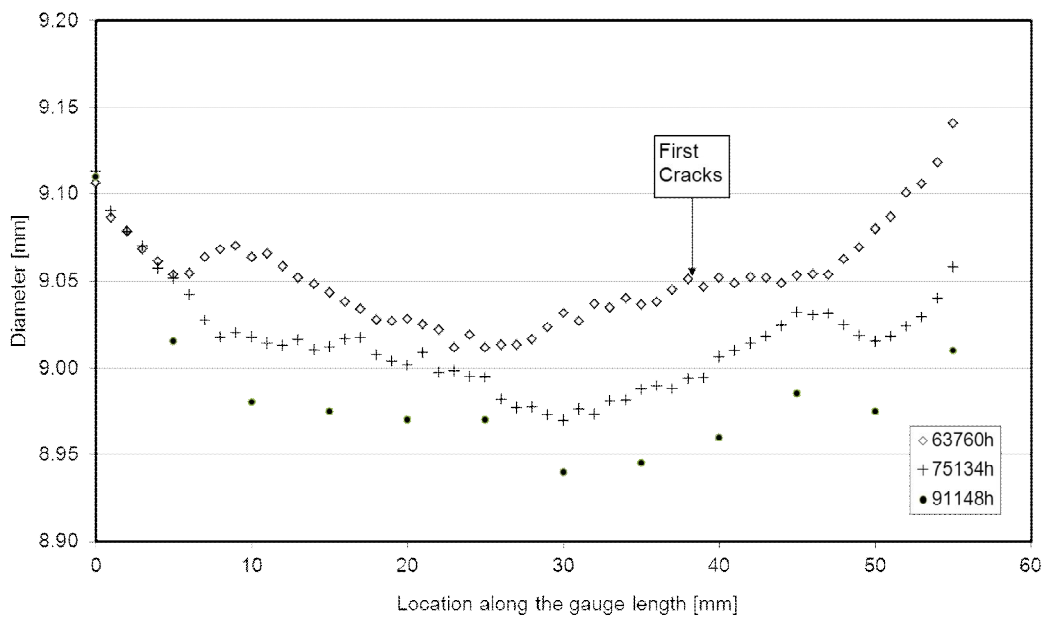Fig. 3. Surface cracks in the uniaxial specimen V1 after 91 148 h at 120 MPa 150°C

Fig. 4. Diameter evolution of the specimen V1 tested at 120 MPa 150°C during three inspections

3.2 Multiaxial testing

The specimen CS3 (Cu-OFP) with a FSW joint has now been running for 45 000 hours at a (plane stress) Mises equivalent stress of 35 MPa at 175°C. After each of the nine testing cycles (5000 h each, currently up to 45 000 h) the test has been 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 20 000 h. It is planned that after reaching a total testing time of 50 000 hours the specimen will be cut to pieces to inspect the centre of the crack front where multiaxiality has possibly enhanced the damage development.

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. The test specimens were machined from a Cu-OFHC bar (diameter 75 mm) with crack growth in the axial direction. The started notch was introduced by wire erosion, which guarantees a straight starter crack front. The notch width after wire erosion using a 0.10 mm wire was 0.16 mm. The test matrix is shown in Table 1. The load line displacement (LLD) curves of these tests are shown in Fig. 5.

In the previous report the crack length versus time dependency had been assumed to be linear. This assumption was checked by performing two more tests at K_I = 8.25 MPa$\sqrt{m}$ at 175°C for Cu-OFHC, see tests CT8 and CT9 in Table 1. The result was surprising as it seems that the crack grows almost instantly by 3 mm and then progresses linearly as a function of time, see Fig. 6. The cracks in OFHC copper seem to branch strongly in short and long-term, reflecting low ductility (see Figs. 17-18), and this could slow down the crack growth rate as the effective stress intensity factor is smaller in a branched crack compared to one dominant crack.

The unexpected behaviour of crack growth (see Fig. 6) makes it impossible to calculate the time to 0.5 mm crack growth which would have been needed for the application of the LICON method. A new interpretation of the method needs to be developed.

Table 1. Cu-OFHC test matrix at 175°C. Tests CT4 and CT5 have been started with the same load as for CT2 but have been interrupted. Size W 50 mm.

| specimen	code	K [MPa√m]	Load [N]	Tresca pl σ	Duration [h]	Max LLD [mm]	Δa [mm]
CT1	y294	8.973	5000	52	1029.7	0.3959	10.25
CT2	y299	8.25	4615.7	47.8	6198.2	0.559	8.71
CT4	y312	8.25	4576.6	47.8	3000	0.3052	5.53
CT5	y314	8.25	4634.2	47.8	980	0.235	3.7
CT8	y354	8.25	4771.63	47.1	484	0.1512	3.83
CT9	y355	8.25	4809.27	46.9	213.7	0.1283	3.282
CT3	y311	7.75	4350.6	44.9	8334.2	0.4944	5.91
CT7	y353	7	4046.9	39.9	2855.2	0.1856	3.553
CT6	y326	6	3354.3	34.8	14733	0.3809	4.37
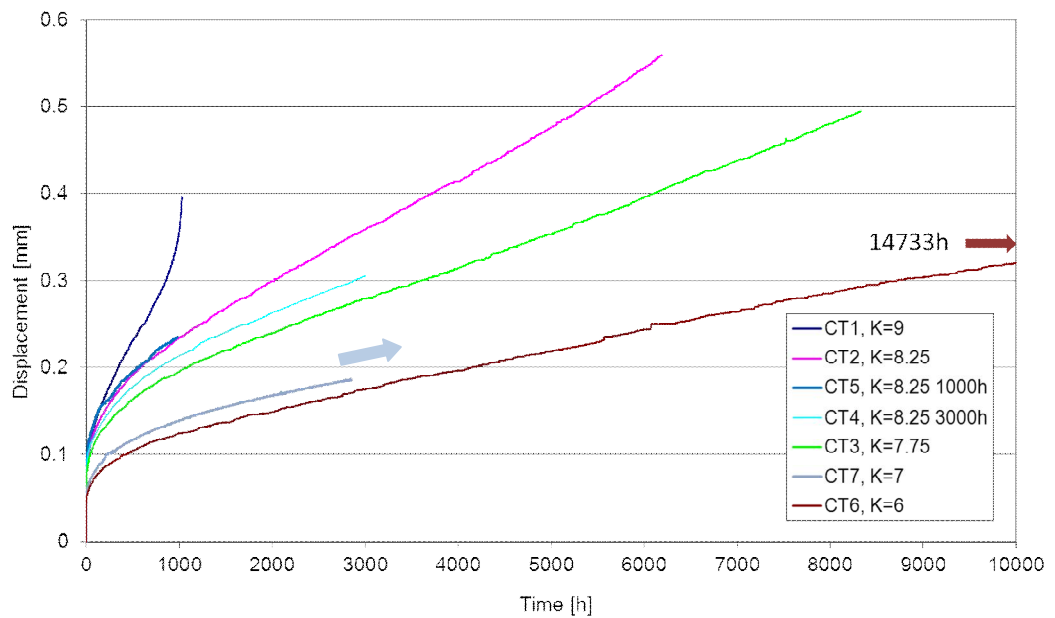
Fig. 5. Load line displacement of the Cu-OFHC CT-specimen test series at 175°C.

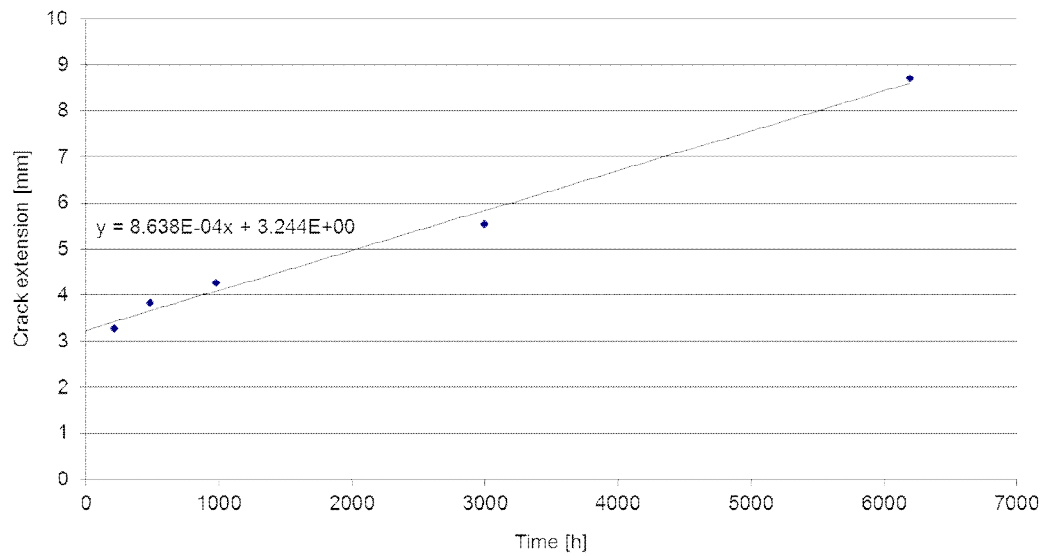*Fig. 6. The calibration curve for crack extension vs. testing time at $K_I = 8.25$ MPa√m at 175°C for Cu-OFHC (CT)*

The dark oxidised areas (see Fig. 7) in the post test fatigue surfaces reported in the previous report have proved to be an anomaly. As the crack in OFHC copper tends to branch very strongly during post-test fatiguing as well as during the creep crack growth test, some fatigue crack surfaces rub against each other. This leads to local heating and local oxidation. This is supported by the comment from the technician doing the post fatiguing that the specimen became much hotter that e.g. steel specimens.
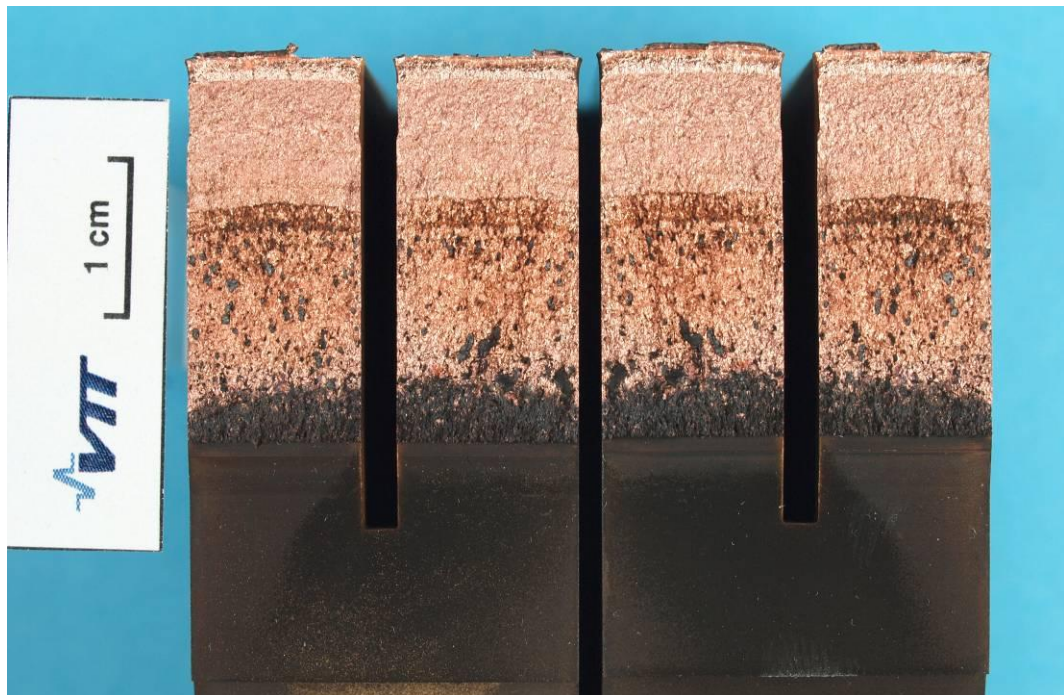

Fig. 7. The oxidised fracture surfaces of Cu-OFHC CT specimen CT5 after testing at 175°C.

A test series for comparison of creep behaviour of FSW and EB welded CT specimens has been completed at identical conditions of K_I = 10 MPa√m (pl. strain VM ref.stress 36 MPa) at 175°C after reaching test durations of 10 000 hours. The starter notch in both specimens is the natural notch. The comparison of load line displacement (LLD) curves is shown in Fig. 8 and the corresponding LLD rates in Fig. 9. Fig. 8 shows that the initial displacement in the EB welded specimen is about 0.7 mm bigger after the first 400 hours of testing, and Fig. 10 shows that the LLD rate in the EB welded specimen is systematically higher than in the FSW specimen. The reason is thought to be related to the much lower level of cold working of the EB welded specimen at the notch tip.
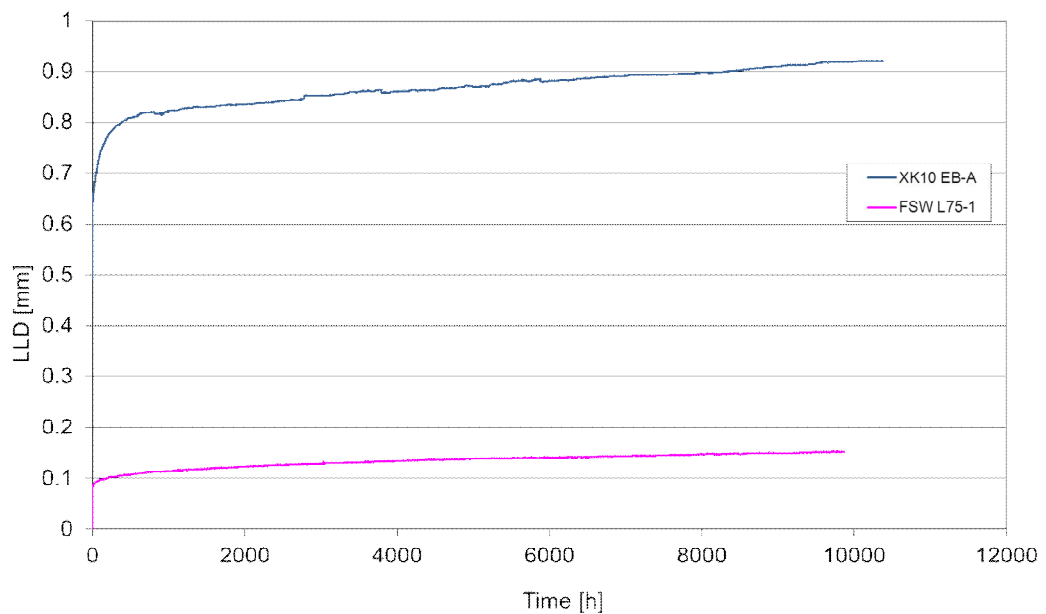

Fig. 8. Comparison of load line displacement curves of FSW and EB welded CT specimens at 175°C at 10 MPa√m

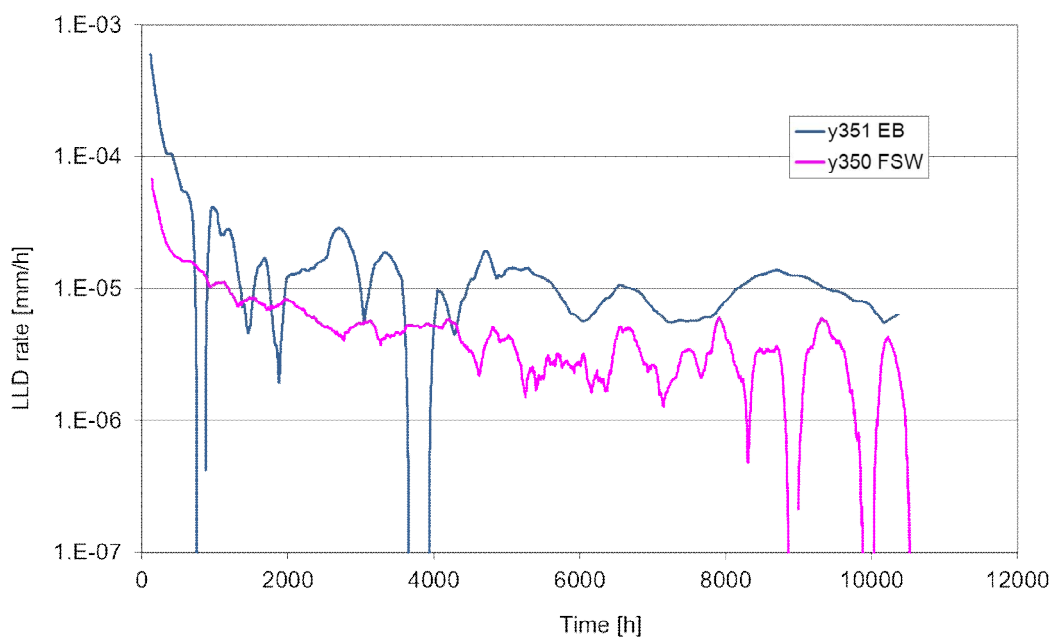*Fig. 9. Comparison of load line displacement rate of FSW and EB welded CT specimens at 175°C at 10 MPa√m*

Another test series was started for EB-welded CT specimen at K_I = 8 MPa√m at 175°C to compare with the long-running FSW CT specimen CS3 (35 MPa reference stress, K_I = 8 MPa√m). The LLD curves are shown in Fig. 10, again demonstrating the higher initial LLD and higher creep rate in the EB welded specimen.

The notched bar (NB) testing series is on-going. The NB test results will be used to demonstrate the effect of multiaxility on lifetime of copper and to compare the results with the CT tests.
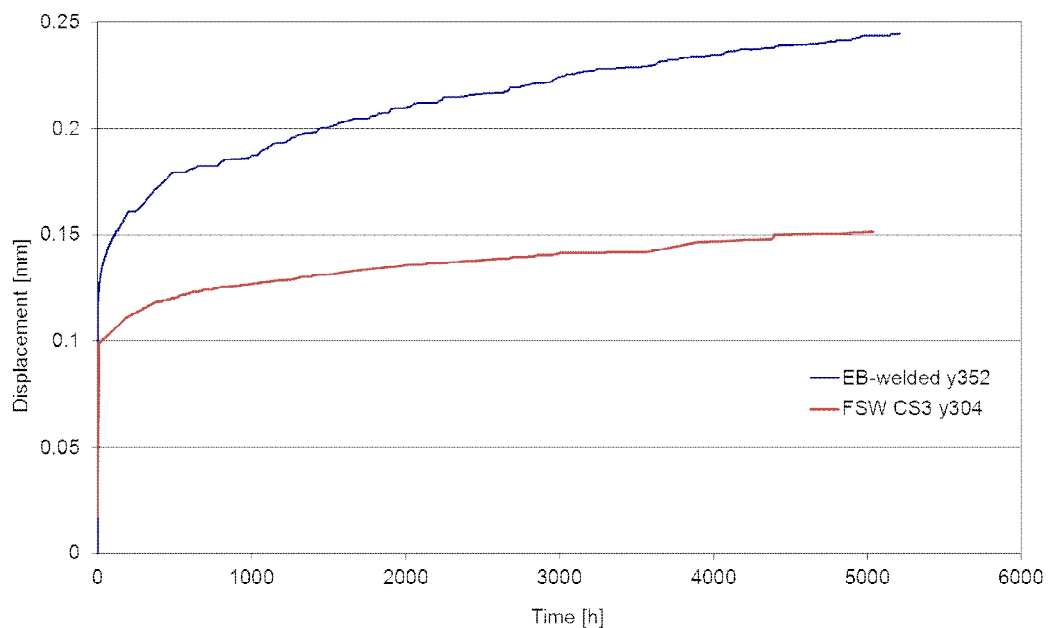

Fig. 10. Comparison of load line displacement curves of FSW and EB welded CT specimens at 175°C / 8 MPa√m

3.3   Metallography of CT specimens

Cu-OFP

The OFP copper CT-specimen (CS3) with a friction stir weld, tested at 175°C at 35 MPa reference stress with interruptions for inspection by optical and scanning electron (EBSD) microscopy every 5000 h, has completed 45 000 h of testing. The cavity density, as evaluated at each inspection of the CT specimen, is shown as a function of testing time in Fig. 11. At the three first 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 significant increase or cavity coalescence up to 45 000 h. The most recent inspections suggest a relatively stable outer surface cavity density of about 600 $1/mm^2$, see Fig. 12. As higher cavity density can be expected in the middle of the specimen where the stress triaxiality is higher, it is planned that after the next 5000 h period of exposure the specimen is sectioned for a detailed study of the damage distribution.

As expected, the cavity density is highest close to the notch tip and decreases quickly beyond a distance of 0.75 mm from the tip. With the resolution of applied technique (SEM) the area with observed cavities extended to some 1.2 mm ahead of the crack tip. In Fig. 13 the weld boundary near the notch tip is shown. It is seen that the cavity density is low in the base material (lower right corner in Fig. 13) and higher in the weld material. However, the cavity density does not seem to concentrate on the weld boundary.

As a trial, the oxidised surface after 40 000 h was inspected before the removal of the oxide and polishing, see Fig. 14. The grain boundaries are revealed quite clearly as well as the grain orientation due to the fact that the rate and direction of oxide growth are dependent on the grain orientation. The future inspections will tell whether this phenomenon can be used to reveal something new of the deformation in the material or about cavity growth. One promising feature is the inspection of the weld root area where a concentration of cavities formed during welding is seen Figs. 15-16.
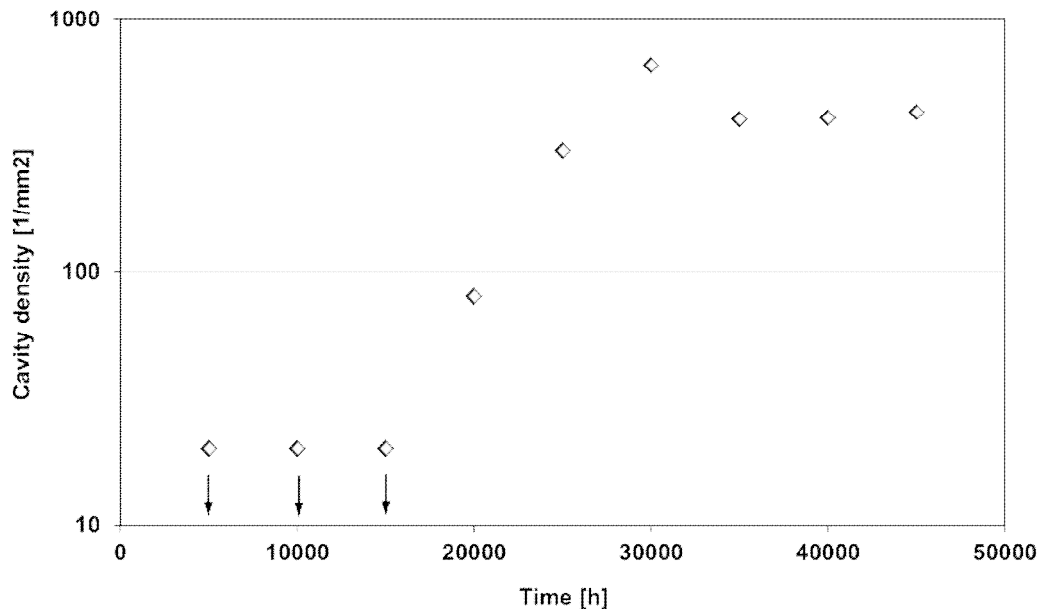

Fig 11. Cavity density in the OFP copper CT-specimen CS3 with friction stir weld at 175°C at 35 MPa reference stress; up to 15 000 h the cavity size was below the limit of detection.
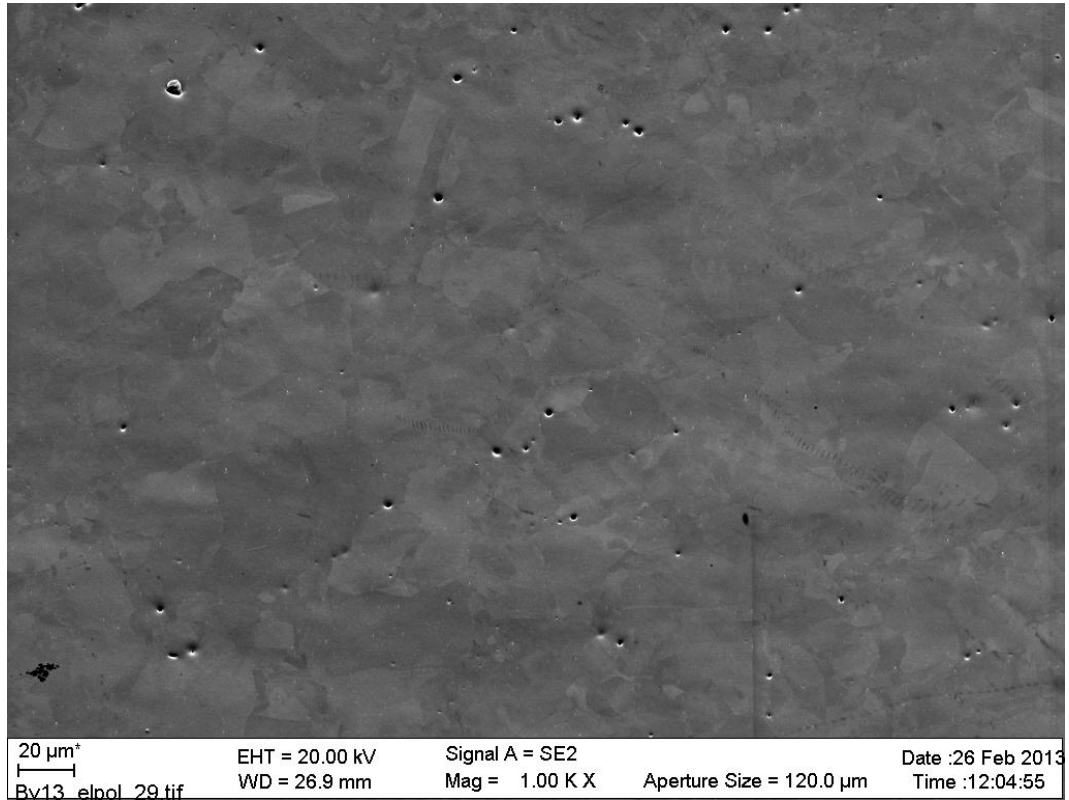
| 20 µm* | | EHT = 20.00 kV | Signal A = SE2 | | Date :26 Feb 2013 |
| Bv13_elpol_29.tif | | WD = 26.9 mm | Mag = 1.00 K X | Aperture Size = 120.0 µm | Time :12:04:55 |

Fig. 12. Cavities at the notch tip of the specimen CS3 after 45 000 h of testing

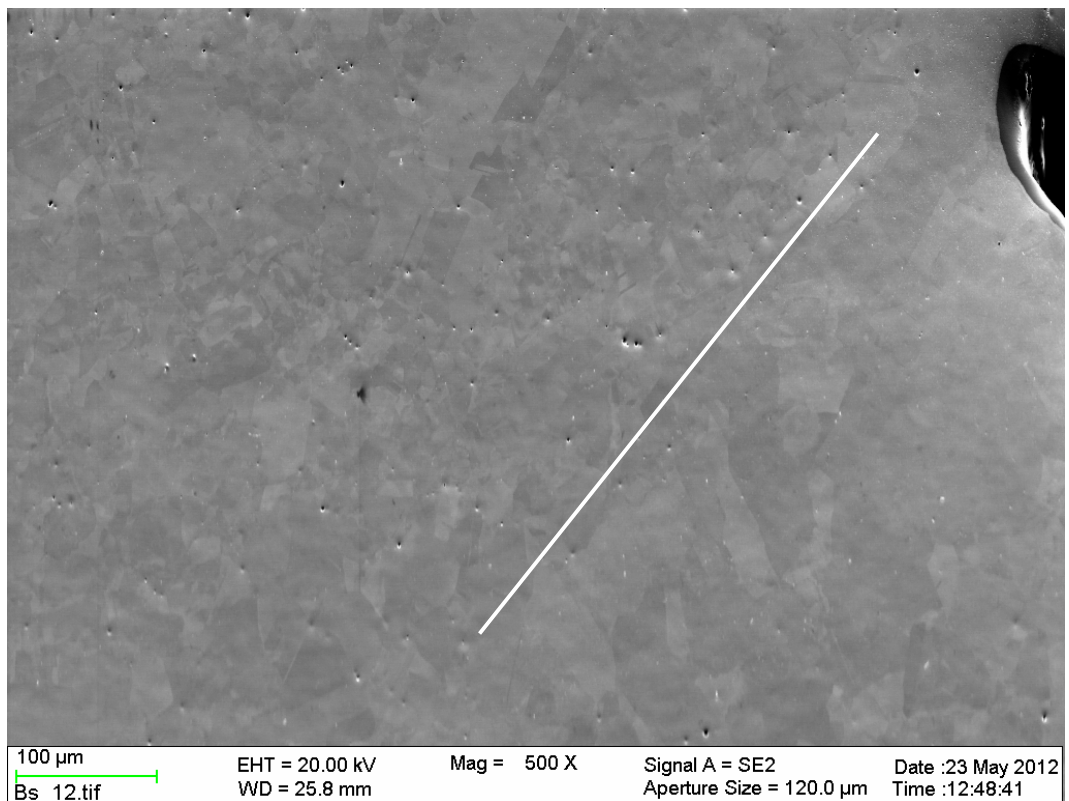| 100 µm | | EHT = 20.00 kV | Mag = 500 X | Signal A = SE2 | Date :23 May 2012 |
| Bs_12.tif | | WD = 25.8 mm | | Aperture Size = 120.0 µm | Time :12:48:41 |

Fig. 13. Cavities at the notch tip of the specimen CS3 after 40 000 h of testing with weld boundary indicated with the white line
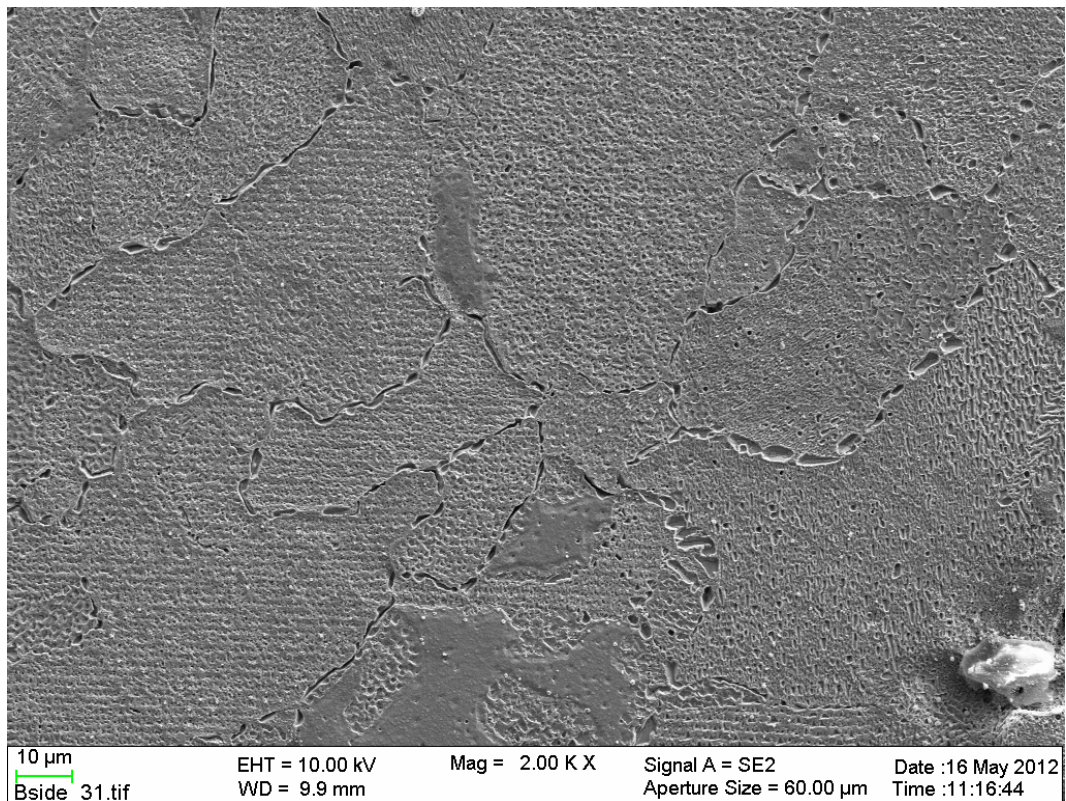
Fig. 14. The oxidised surface of the specimen CS3 near the notch tip after 40 000 h of testing, notch direction vertical, loading direction horizontal
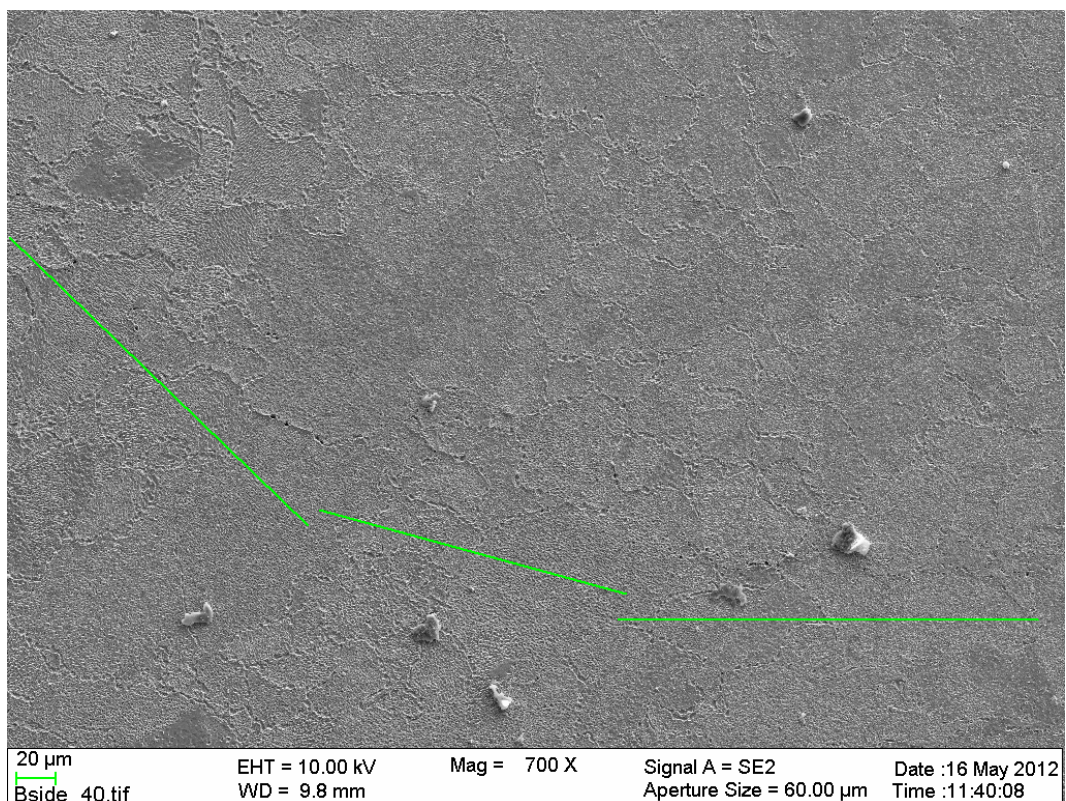

Fig. 15. The oxidised surface of the specimen CS3 near the notch tip after 40 000 h of testing, at the weld root area 8.3mm left from the notch tip, notch direction vertical, loading direction horizontal, weld boundary indicated with lines
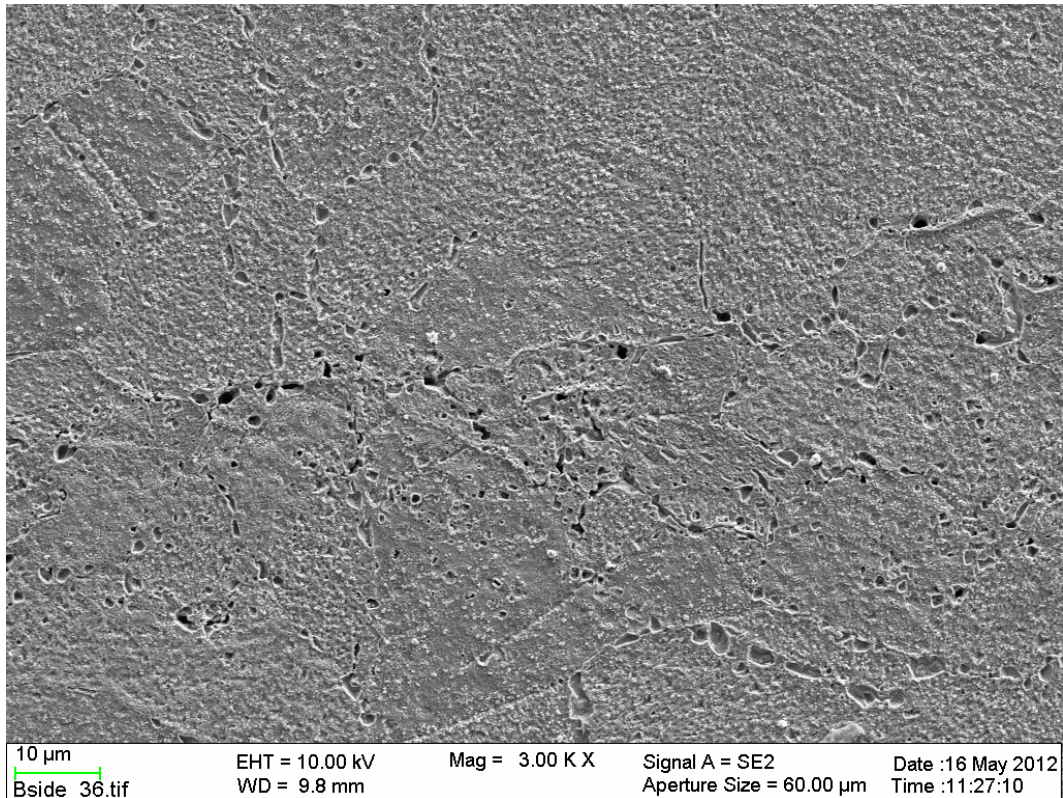
Fig. 16. Enlargement from Fig. 15

Cu-OFHC

Slices were removed from the two additional Cu OFHC CT specimens for metallographic inspection of the crack growth. Instead of the expected short crack growth the both specimens showed a rapid crack extension beyond 3mm, see Figs. 17-18. The crack starts to branch almost immediately after initiation and this is expected to reduce the effective stress intensity factor of the notch and lead to slower crack growth rate, see Fig. 6.
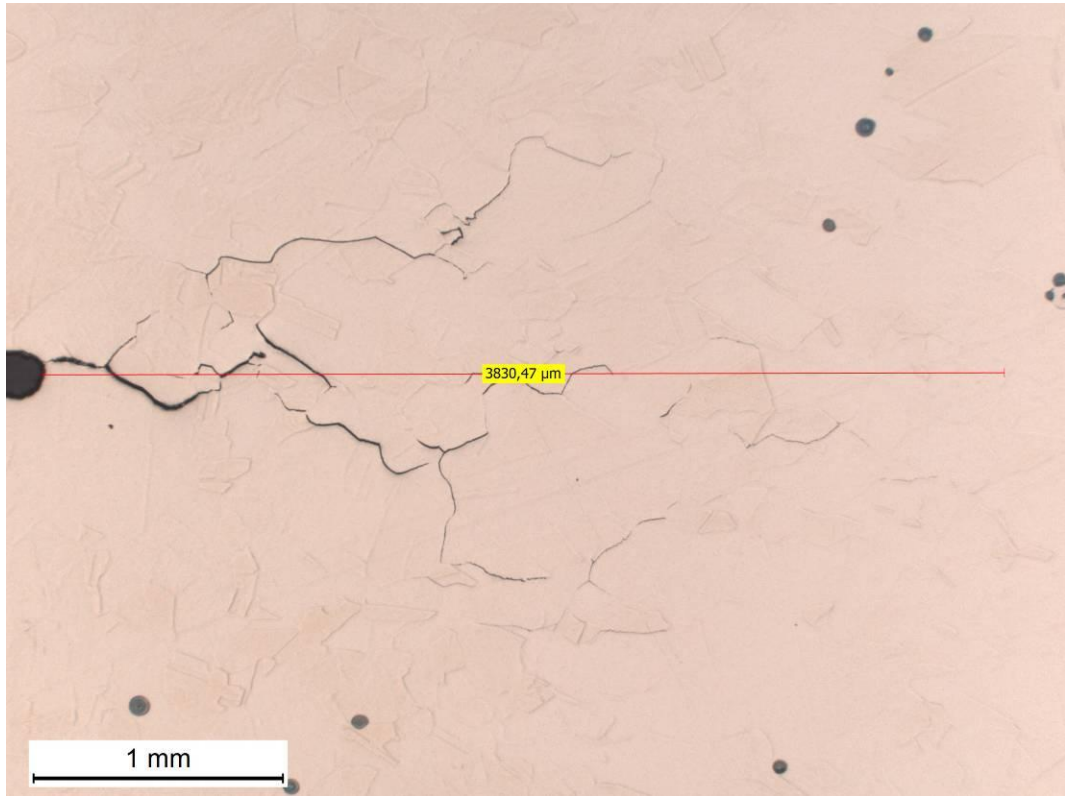
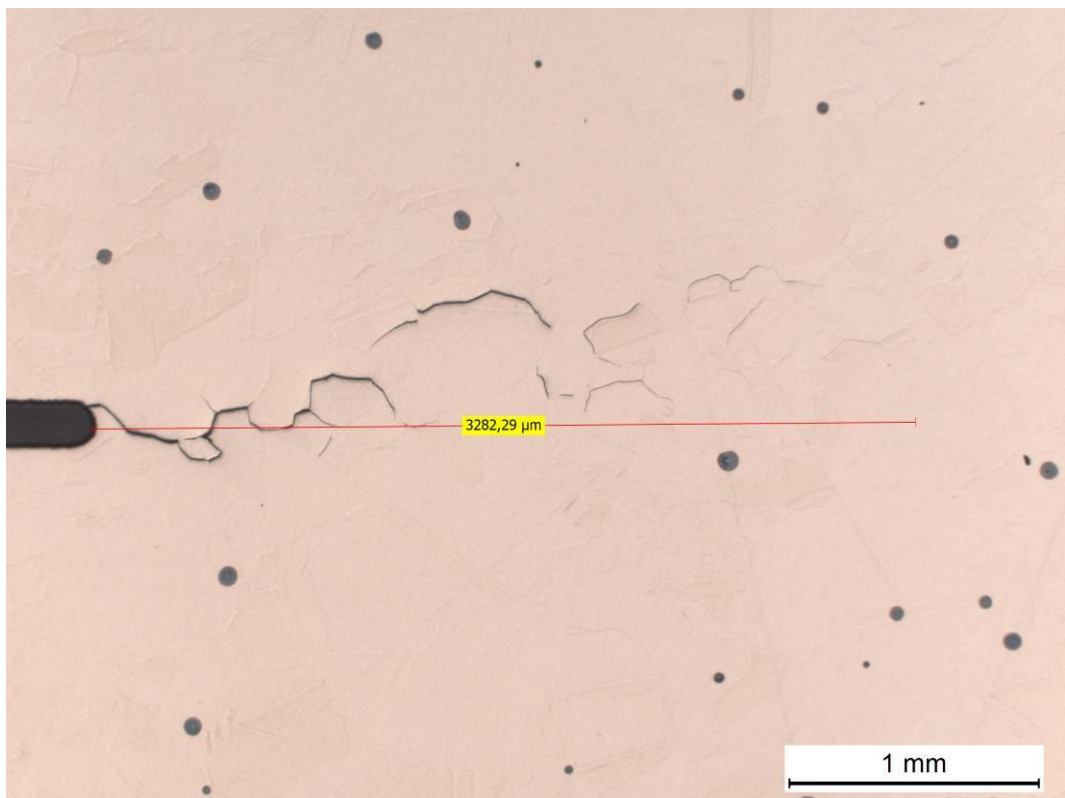*Fig 17. Crack branching in a Cu-OFHC specimen CT8 after 484 h of testing at 175°C, un-etched sample*

Fig 18. Crack branching in a Cu-OFHC specimen CT9 after 214 h of testing at 175°C, un-etched sample

3.4 Creep rupture modelling

Copper is initially soft but strongly strain hardening material, and somewhat challenging to model due to the scatter in observed creep strength at high stresses that are necessary when testing for sensible test durations at temperatures close to the repository conditions. Therefore the Wilshire rupture model that uses normalization to the tensile strength is used here. The selected Wilshire equations /3/ has provided a methodology for direct fitting and prediction of minimum strain rate, time to strain and time to rupture. The method needs additional tensile test data at the creep test temperatures for stress normalization. The model avoids the varying stress exponent of conventional models, and the creep activation energy can be defined in a straightforward way. By using the Wilshire model the long term predictions of both rupture and strain have been improved.

The Wilshire equation for time to rupture t_r at stress σ and temperature T 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 (determined as in Fig.19) for OFP and OFHC are presented in Table 2.
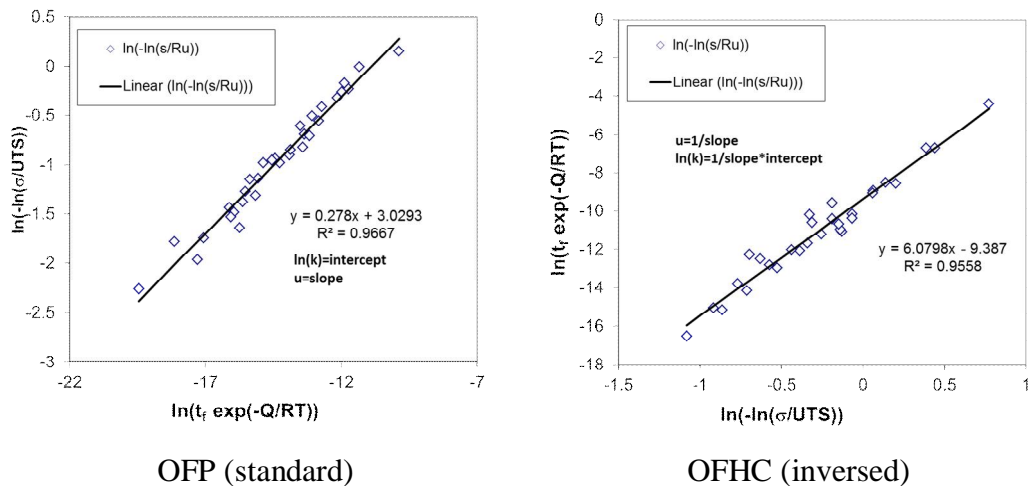

OFP (standard)   OFHC (inversed)

Fig. 19. Linear regression determination of parameters k and u for OFP and OFHC copper

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 /5,6/.

Table 2. 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}	23.7276
u_{ref}	0.2876
$\sigma_{TS\text{-ref}}[T(°C)]$	216-0.339·T(°C) MPa
OFHC apparent activation energy, $Q*_{c\text{-ref}}$	61 400 J/mole
k_{ref}	4.6831
u_{ref}	0.1645
$\sigma_{TS\text{-ref}}[T(K)]$	191.31+0.65634· T(K)-0.00185· $T(K)^2$+0.0000010185·$T(K)^3$ 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. In Fig. 22 OFP and OFHC copper models are presented for strength comparison with the same activation energy forced on the OFHC. The tensile strength used for the Wilshire model strength normalisation is presented in Fig. 23.
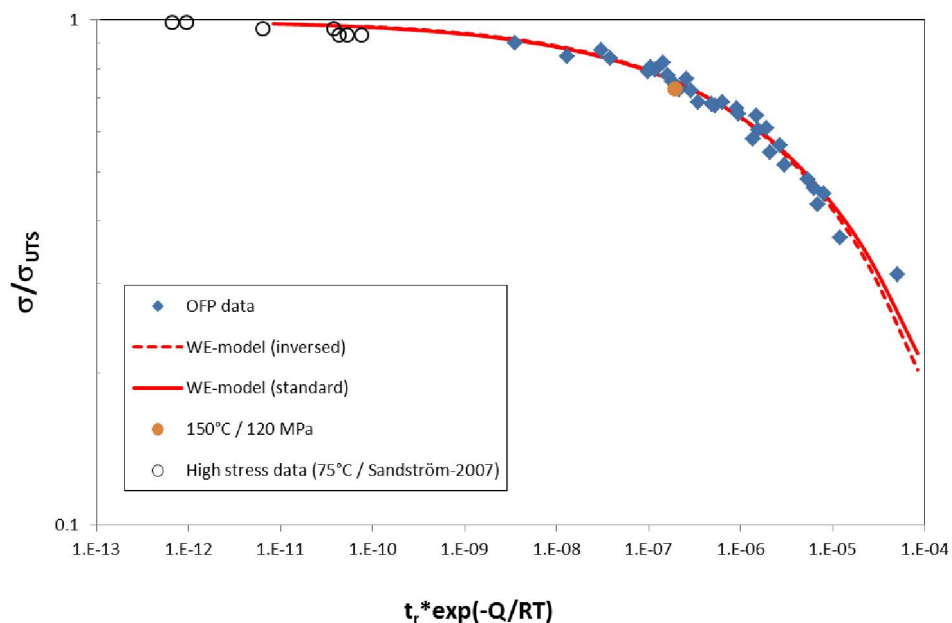

Fig 20. Wilshire model based life predictions for base material (BM) of OFP copper; the large red dot is the running 150°C/120 MPa uniaxial test (running at 10.4 years, predicted life 16.2 years when Qc*=95 kJ/mol).
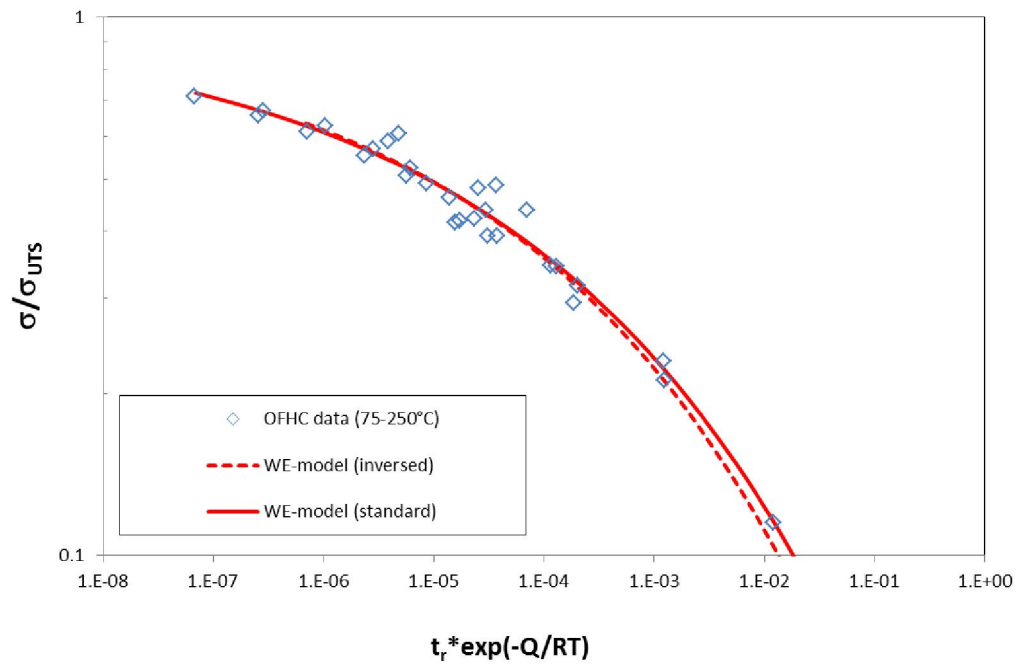
Fig 21. Wilshire model fit to creep rupture data of OFHC copper with Qc*=61.4 kJ/mol
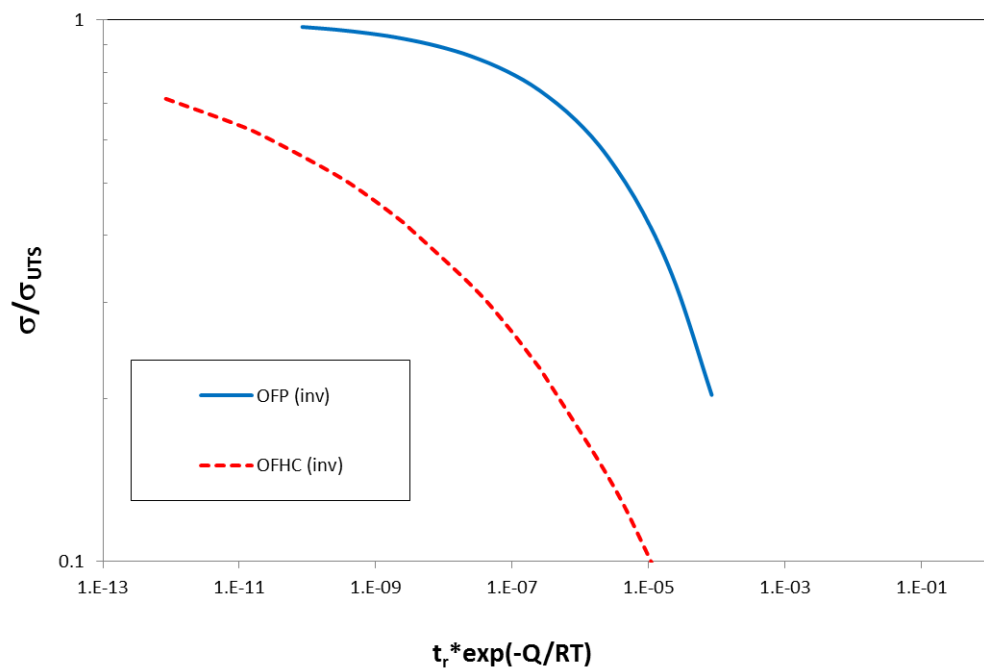

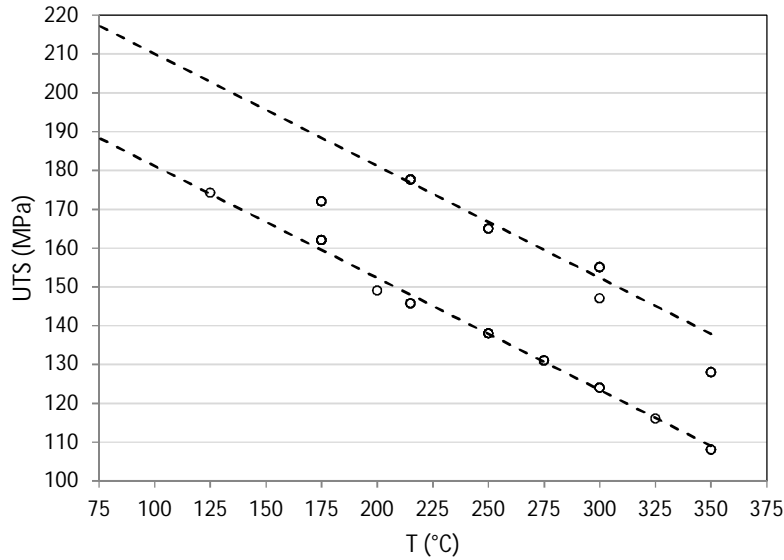*Fig 22. Comparison of OFP and OFHC copper with forced Qc* set at 95 kJ/mol for the OFHC.*

Fig 23. Temperature dependence of tensile strength (UTS) of OFP copper (lower line: UTS = 210 – 0.289·T (°C)

3.5 Creep strain modelling

The capability of the LCSP model to predict well the strain rates /4/ can be taken to suggest inversely a fair ability to predict time to rupture from relatively early strain data of unfailed specimens. The strain and strain rate dependence of stress, temperature and time can be described by the LCSP functions:

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

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

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

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 /6/ are presented in Fig. 24. The available data seems to be compatible with the Monkman-Grant expression for time to rupture and minimum strain rates, but with fair amount of scatter towards longer creep life (Fig. 25).
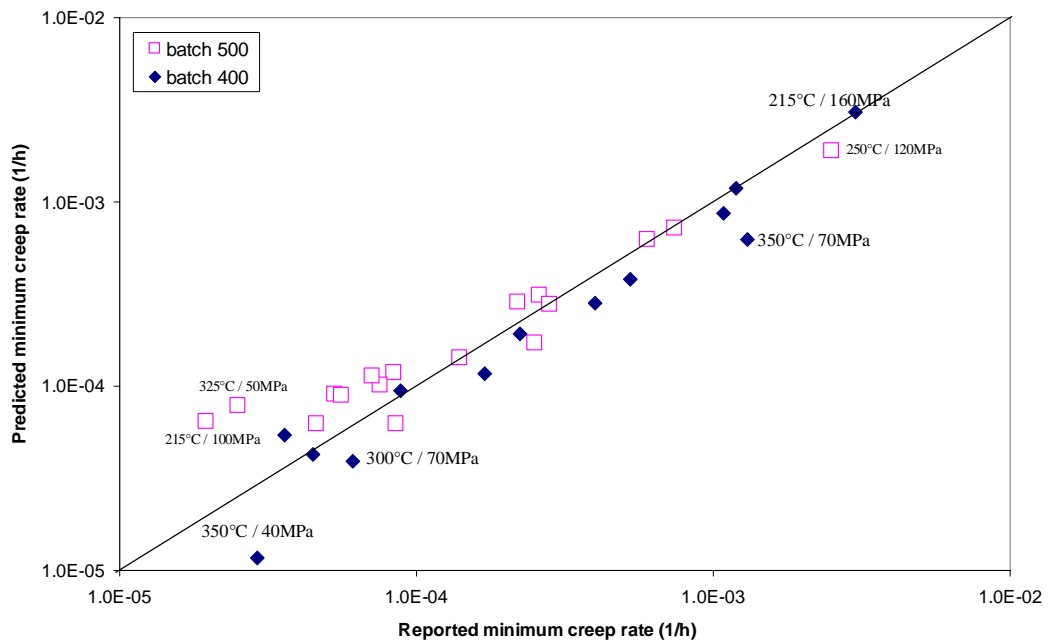
Fig 24. LCSP predicted OFP copper minimum strain rates against the measured ones for batch 400 and 500 in [14]; the diagonal line represents perfect fit.
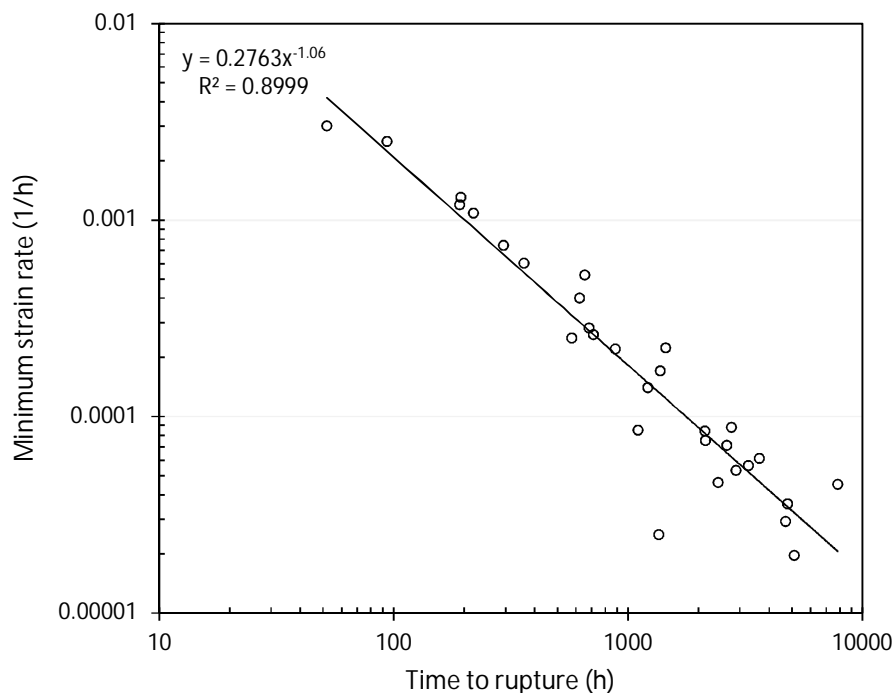

Fig 25. Monkman-Grant plot of the Cu-OFP creep data

The LCSP model can be considered as an equally suitable but simpler than the classical θ-model /7/. 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. It should be noted that the available creep test data appears particularly to lack results from low stress regime with low initial strain levels. This is unfortunate because it is one of the main factors introducing uncertainty to long-term life prediction.

3.6 FE analysis of the copper overpack

The LCSP model is implemented in the Abaqus 6.12-1 (Simulia, 2012) finite element analysis package via a user subroutine interface. The subroutine contains the implicit and explicit time integration procedures and the multiaxial material model follows a normality preserving constitutive model. The subroutine is called at material points of the FE mesh for a specific increment and as a result it returns the integrated creep strain increments. The LCSP model is always accompanied by a time-independent elastic-plastic material model since an accurate description of the overall plastic response is important for accurate resolution of strain rates. Multi-linear stress-strain curves are utilized with an isotropic incremental plasticity model. The implementation is applied using a finite strain description for deformation. Creep weld strength factors are applied to material regions within the subroutine by dividing the applied stress with their specific value, yielding typically an increase in creep strain rate for different weld regions. The derivation of the finite element analysis Fortran code is performed by computing these terms using Mathematica 8.0 (Wolfram Research, 2011) and writing the user subroutine via a Python (open source code) module.

The long-term creep analysis is carried out by exposing the canister to an applied external pressure of 14 MPa at a temperature of 80°C the elastic-plastic material model being active. Then an isothermal simulation is performed the viscoplastic creep model being active with a WSF of 0.95 for the FSW weld. Weld residual stresses are not included in the current analyses.

A 20 degree slice of the copper canister from half-length upwards is constructed containing the FSW weld and its geometry, the weld being a single material region, see Fig. 26. Symmetry constraints are enforced in a polar coordinate system and the model is fixed at its bottom in the axial direction of the cylinder. For radial and axial gaps between the insert and the copper shell and the groove between the lid and cylinder of the canister contact constraints are introduced. A finite sliding Lagrangian contact formulation is applied with frictionless sliding. A fairly coarse mesh of quadratic 20 node brick elements with reduced integration is constructed in order to facilitate the lengthy time integration to several tens of thousands of years. Stable incrementation ranges from below an hour to several tens of thousands of hours, and usually a time increment count in the range of several millions is required. Somewhat coarse meshes also introduce a degree of non-localness for the LCSP material model, which especially for the copper in question known to have a high primary creep rate response is a feasible property.
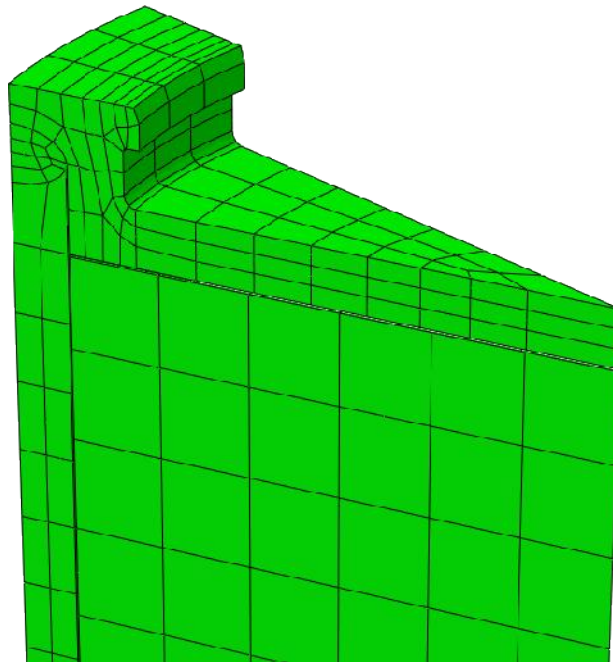
Fig. 26. The mesh used in the initial analysis

The maximum principal stress distribution after 0.3 hours is shown in Fig. 27 where the maximum stress point is inside the FSW in the compressive stress region is an anomaly. Compression of the lid against the inner vessel causes tensile stresses in the middle of the upper surface of the lid. Surprisingly the inner corner of the lid is not heavily stressed. Most heavily stressed locations are the FSW joint notch tip region and the outer surface of the FSW as shown in Fig. 27. The analysis also suggests that the cylinder will come into contact with the insert already during loading.

The tensile stress on the FSW outer surface is in the order of 80MPa as shown in Figs. 27 and 29. After 10^8 hours (11 400 years) the stresses have relaxed to a very low level, see Figs. 28 and29.

These initial results suggest that the stresses relax very rapidly at the outer perimeter of the lid, where the critical stress areas are located. In Fig. 29 the rapid decrease of the maximum principal stress in the middle of the FSW on the outer surface is shown. The initial stress peak relaxes quickly and then the stress level stays practically constant up to 10^5 hours (11 years). During this time the cylinder creeps against the insert and this keeps the stress level in the FSW constant. After 10^5 hours the cylinder is in contact with the insert except close to the lid where the air gap remains. A very similar trend is observed on the lid/cylinder contact point as shown is Fig. 30. The lid/cylinder contact point is the lid corner which is compressed against the cylinder. A maximum principal strain of 3.1% is reached after $4.92*10^8$ hours (56 100 years), see Fig. 31. This is also very much lower than what was reported in /2/. In the middle of the FSW on the outer surface the strain reaches a value of only 0.42% during loading, and this value does not increase much during the long exposure, see Fig. 32.
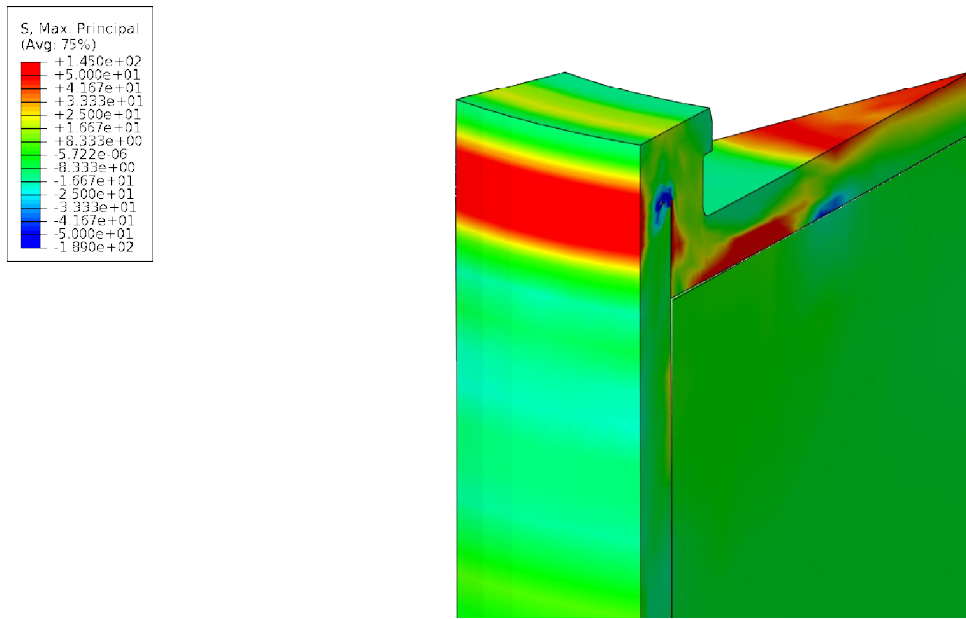
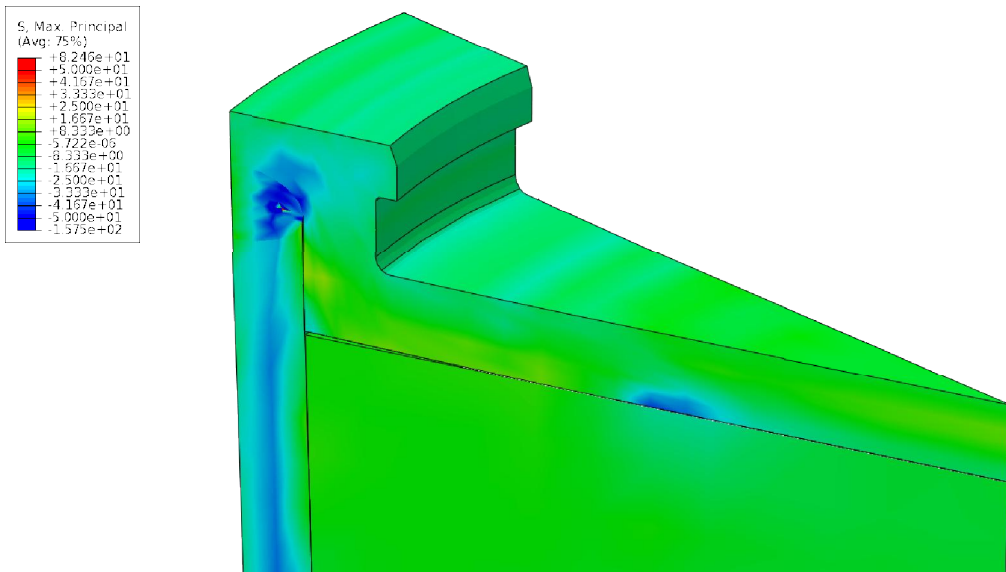*Fig. 27. Maximum principal stress distribution after 0.3 h*

Fig. 28. Maximum principal stress distribution after 10^8 hours (11 400 years)
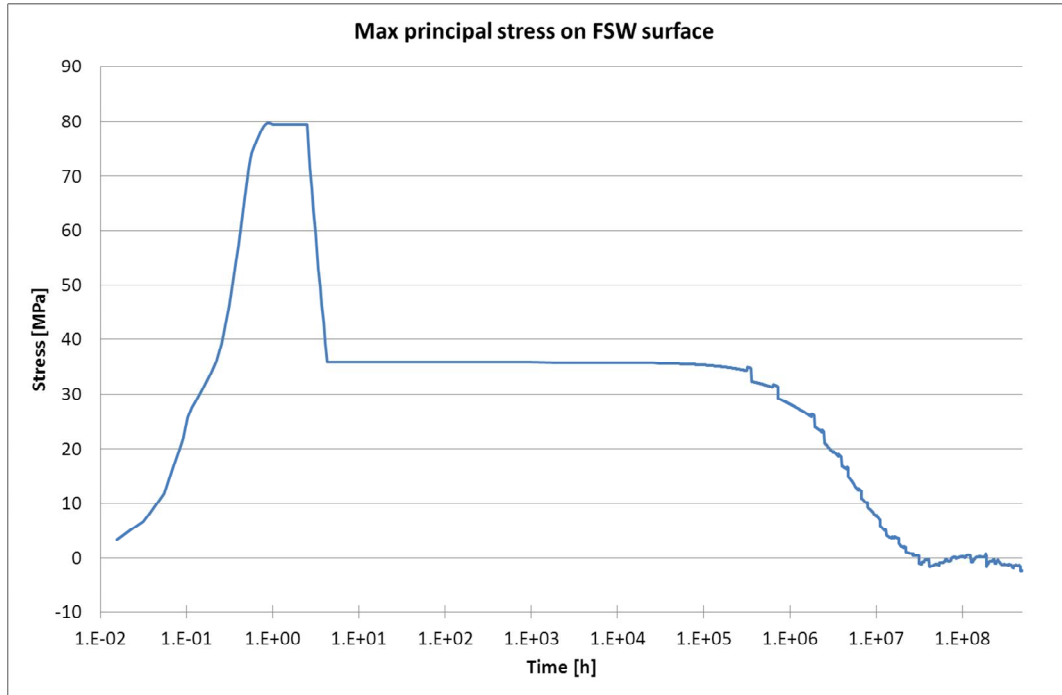
Fig. 29. Maximum principal stress as a function of time on the FSW outer surface
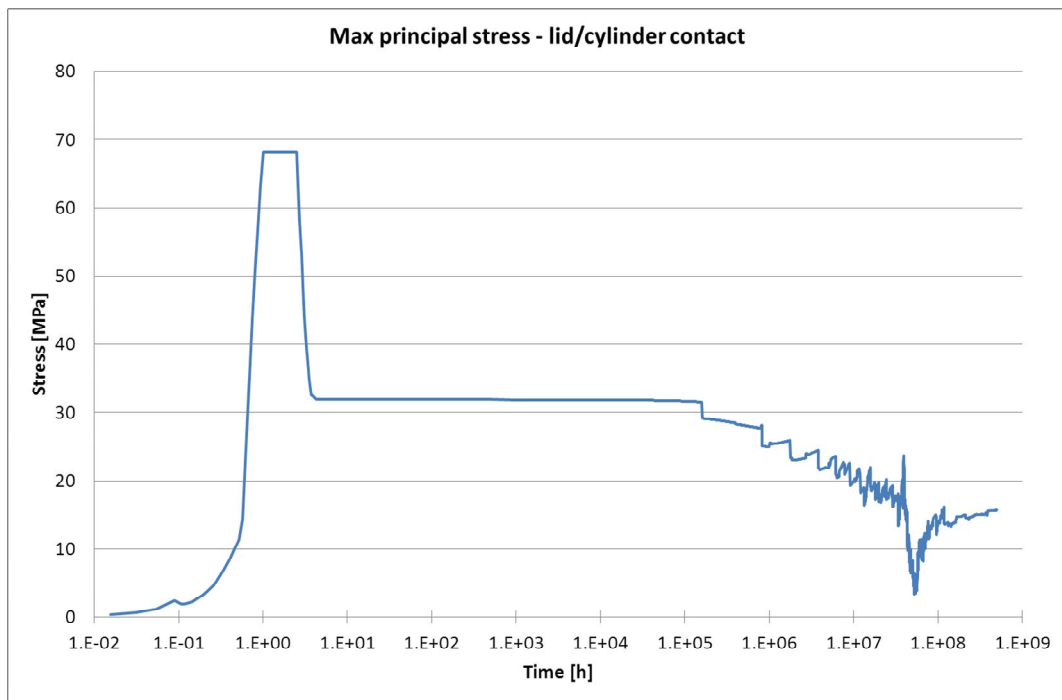

Fig. 30. Maximum principal stress as a function of time on the lid/cylinder contact point
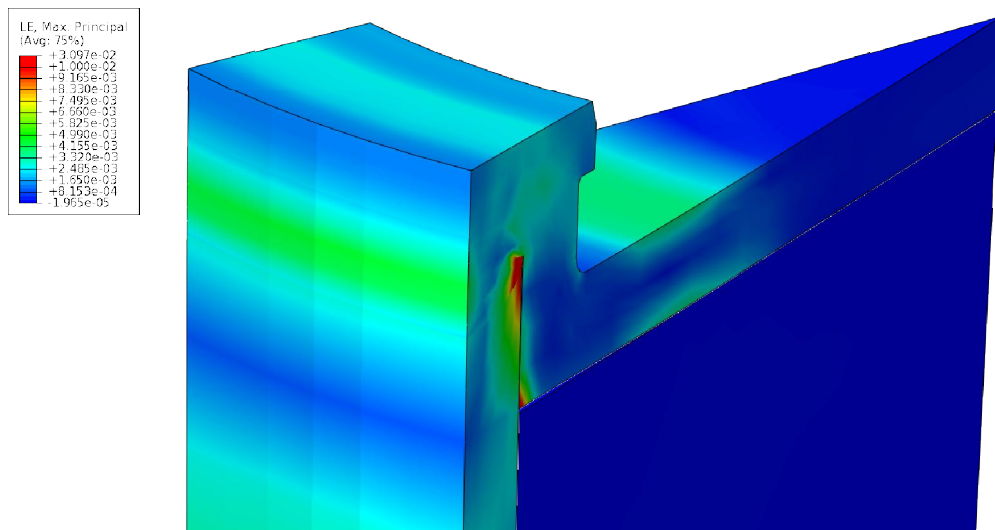
Fig. 31. Maximum principal strain distribution after 4.92*10⁸ hours (56 100 years)
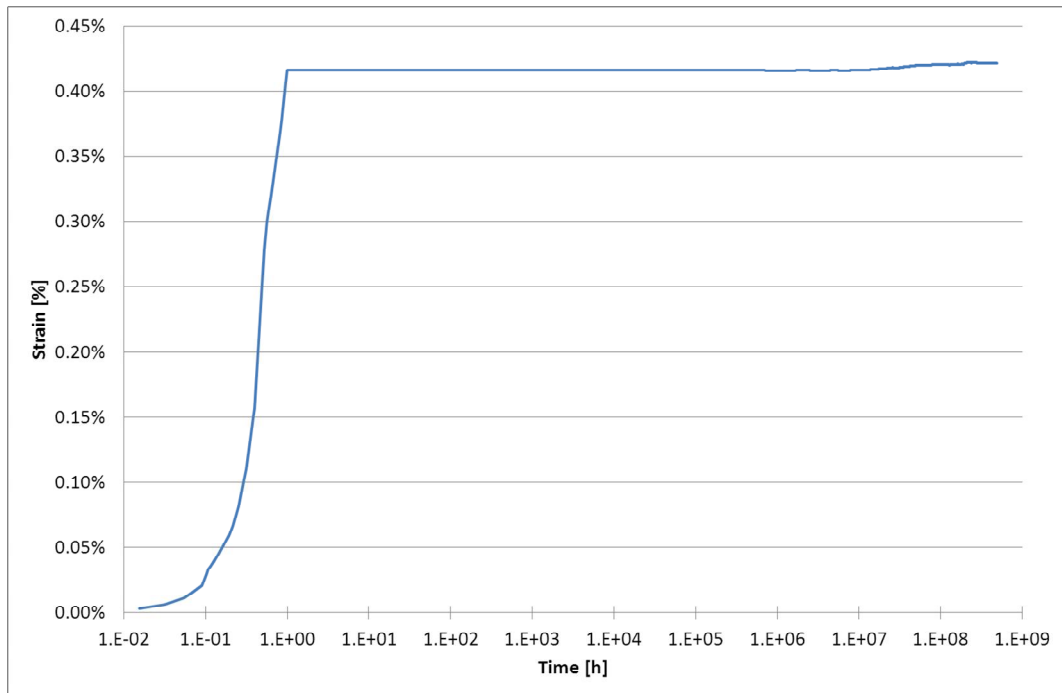

Fig. 32. Maximum principal strain (tensile) evolution on the outer surface of FSW

4 Discussion

The relaxation of the stresses is somewhat expected as the loading case of the copper overpack is forced displacement when the canister is compressed against the core by the hydrostatic stress. The rapid relaxation of stresses is, however, in contradiction with the results shown in /2/. This raises the question whether the creep models used in the analysis are capable of predicting relaxation, which has traditionally been a challenge for standard creep models which have been developed for "forward creep" where the stresses normally increase as a function of time. In relaxation, however, the stresses decrease, and this creates a challenge for creep models. For this reason traditionally dedicated creep models have had to

be developed for relaxation, and this could well be the case for the overpack as well.

To verify the validity of the creep models, a round robin exercise has been proposed so that the Swedish and Finnish creep models would be used to predict the following cases that are also verified experimentally:

1) Uniaxial relaxation test (temperatures e.g. 75°C and 175°C, to be decided)

2) Relaxation test of a ring (temperatures as above)

The FE model predictions should be completed before the tests. This proposal has received initial positive response.

In 2013 the mesh will be refined and the tensile anomaly inside the compressive stress region near the joint tip will be eliminated. Also the effect of loading rate will be studied in more detail as the loading rate has a large impact on the stress levels that develop in the elastic-plastic calculation. With instantaneous loading high initial stresses and strains will develop before stress relaxation. With a slow loading rate the stress peak is substantially reduced, but creep starts already during loading. This will have an effect on the predicted life. One of the important conclusions is that it is essential to be able to model accurately the initial part of the creep curve (and corresponding initial part of other loading configurations, like relaxation) to successfully and accurately predict the long-term life.

In 2013 a diploma thesis work will be done on comparison of round notched bar and an alternative octahedral specimen, which is easier to machine, but does not yet have the necessary reference stress analysis available. The thesis work is aimed to provide this.

5 Publications

J. Rantala, P. Auerkari, J. Salonen, S. Holmström, A. Laukkanen and T. Saukkonen, Creep damage development in canister copper, 12th International Conference on Creep and Fracture of Engineering Materials and Structures (Creep 2012), May 27-31, 2012, Kyoto, Japan

This work is a part of the doctoral thesis of Juhani Rantala, dealing with the effect of multiaxiality on creep damage initiation.

6   Conclusions and summary

Base materials and FSW welds of OFP copper have been subjected to creep experiments at low levels of temperature (150-175°C) and stress (35-120 MPa). Multiaxial loading of the CT specimens, tested up to 45 000 h (5 years) at 175°C continues to show creep damage evolution as recovery zones at stressed grain boundaries and grain boundary cavitation close to the notch/crack tip. In contrast, fast evolving intergranular creep damage, crack branching and low ductility were confirmed for CT specimens of Cu-OFHC tested up to 14 700 h (1.7 years), with multi-axiality and low ductility resulting in a strong life reduction of life at low stress (longer term) testing. Multiaxial tests on EB-welded CT specimens have also been started to facilitate comparison of material behaviour with FSW welded specimens.

In comparison, 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 a testing time of 91 148 h (10.4 years). For damage modelling it is of interest that this specimen has also shown distributed microcracking in interrupted testing. The observed 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 modelling and FE analysis for life assessment.

The material model (LCSP) was updated according to the test results and implemented to FEA code. The results of FEA suggest sustained concentration of tensile stress and strain close to the external (FSW) weld surface, with potential for locally concentrating damage. The maximum principal strain predicted was about 3 % located near the FSW joint tip after 56 100 years. Otherwise, the predicted stress distributions differ markedly from those suggested previously elsewhere, and further work is suggested to clarify the discrepancy. In particular, the short and long-term relaxed stress levels are substantially lower than those previously predicted. It is essential to be able to model accurately the initial part of the loading response to successfully and accurately predict the long-term life.

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