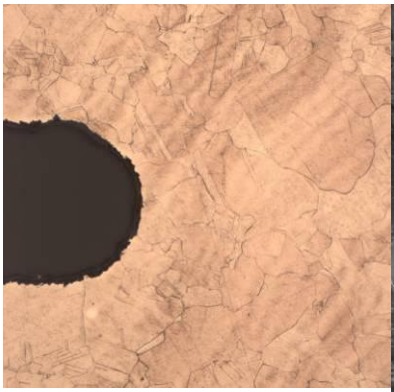
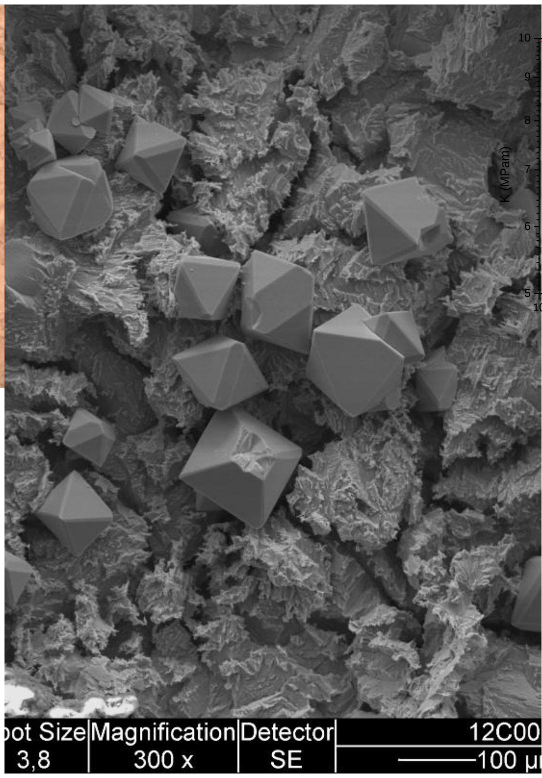
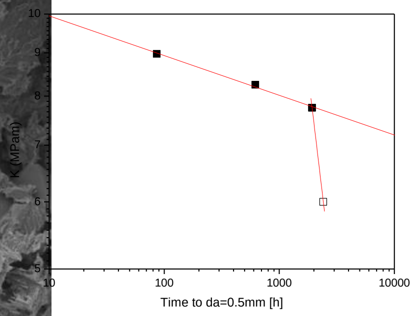






KYT 2014 / MICO

Material integrity of welded copper overpack – Final report 2011

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

Confidentiality: Public

Report's title	
Material integrity of welded copper overpack – Final report 2011	
Customer, contact person, address KYT 2010	Order reference
Project name MICO2011	Project number/Short name 73824
Authors Juhani Rantala, Jorma Salonen, Pertti Auerkari, Stefan Holmström / VTT; Tapio Saukkonen / Aalto University	Pages 30
Keywords creep, corrosion, copper, repository, life	Report identification code VTT-R-01384-12

Summary

Base material 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 35 000 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 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, with multiaxiality and low ductility resulting in a strong reduction of life when testing times are longer than 2000 h.

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 83 200 h. 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.

Change of loading pin material largely prevented previously observed heavy general corrosion in the combined corrosion and creep testing of welded CT specimens (OFP copper) immersed in aerated simulated Olkiluoto groundwater at 90°C. However, some pitting corrosion was still found, probably due to galvanic corrosion that needs to be excluded.

Confidentiality	Public

Espoo 28.2.2012

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 1 copy
VTT 1 copy

Preface

This report provides the final annual report of the project “Material integrity of welded copper overpack” (MICO2011), including and summarising the experimental, modelling and life assessment activities as well as the results and status of the project up to end of 2011. The project is a part of the Finnish national research program on nuclear waste management, 2011-2014 (KYT2014). The financial support and other guidance by this program, STUK (Finland) and SSM (Sweden) are gratefully acknowledged.

Espoo, February 28, 2012

Authors

Contents

Preface 2

1 Introduction 4
1.1 Background 4
1.2 Objectives 5

2 Materials and methods 5

3 Results 6
3.1 Uniaxial testing 6
3.2 Multiaxial testing 8
3.3 Combined creep and corrosion (CT) testing 16
3.4 Metallography 21
3.5 Creep modelling 25
3.6 Optical strain measurement 26

4 Publications 28

5 Conclusions and summary 28

References 29

1 Introduction

1.1 Background

The technical challenge in assessing the integrity of the copper overpack of the spent fuel canister 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 common extent of extrapolation from laboratory experiments to real service conditions.

In the repository, 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 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 2011-2014 (KYT2014). The project also includes specific issues requested and 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 2011 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. More recently a full FSW joint (L75) has been received. 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 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. 1) 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 thickness (B) of each CT specimen is 25.00 mm. The CT specimen notch for welded OFP copper applied the natural gap tip of the joint, while the notch for (parent) Cu-OFHC material used 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 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]. Impression creep method has been applied for Cu-OFP base material and optical strain measurement method (SPICA) for strain measurement at the CT specimen notch tip region.

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.

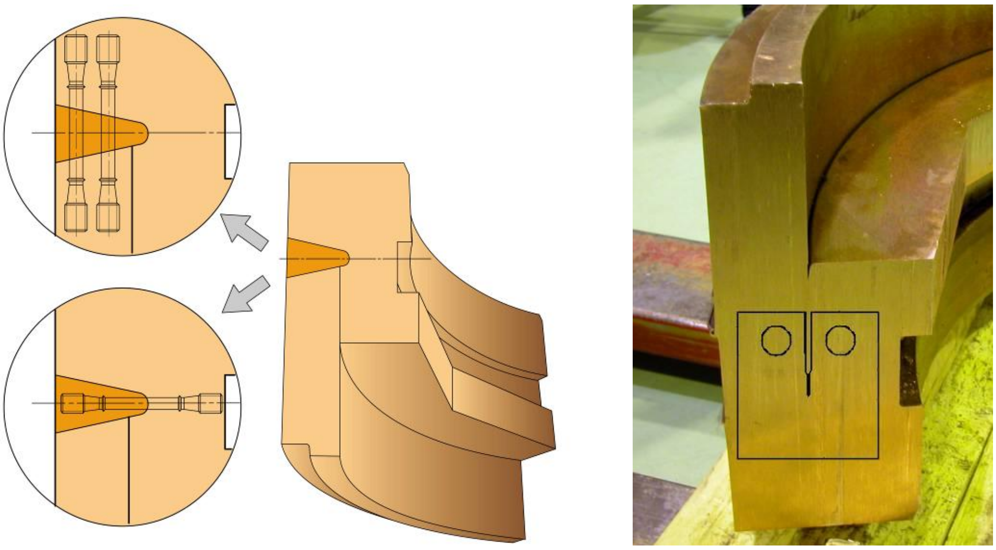


Fig 1. Extraction (Cu-OFP) of a) uniaxial and b) CT specimens for testing

3 Results

3.1 Uniaxial 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 83 200 h (9.5 years) of testing time and a true strain of beyond 10%. At 63 760 h the test was interrupted for visual inspection and physical measurements. At that point small surface cracks were observed. Measuring the specimen diameter along the gauge length indicated still rather uniform elongation without necking, and the observed surface cracks were not located in the region of the smallest diameter. After inspection, the test was continued at the same loading conditions as before. When the test was again interrupted at 75 134 h, the previously detected surface cracks had not grown, but many more similar cracks had appeared (Fig. 2). 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 63 760 h, but no real necking had yet started.

The test K3 at 200°C/70 MPa is running at 33 000 h. All testing results have been used to support creep modelling and to set the initial loading levels in multiaxial (CT) testing.

The impression creep test facility has been applied for copper base material, and an example curve is shown in Fig. 3. The results of the impression creep testing provide the primary to minimum creep rates at the test load. When more curves will be acquired the results can be compared against the usual uniaxial creep results to support creep modelling for e.g. welds.

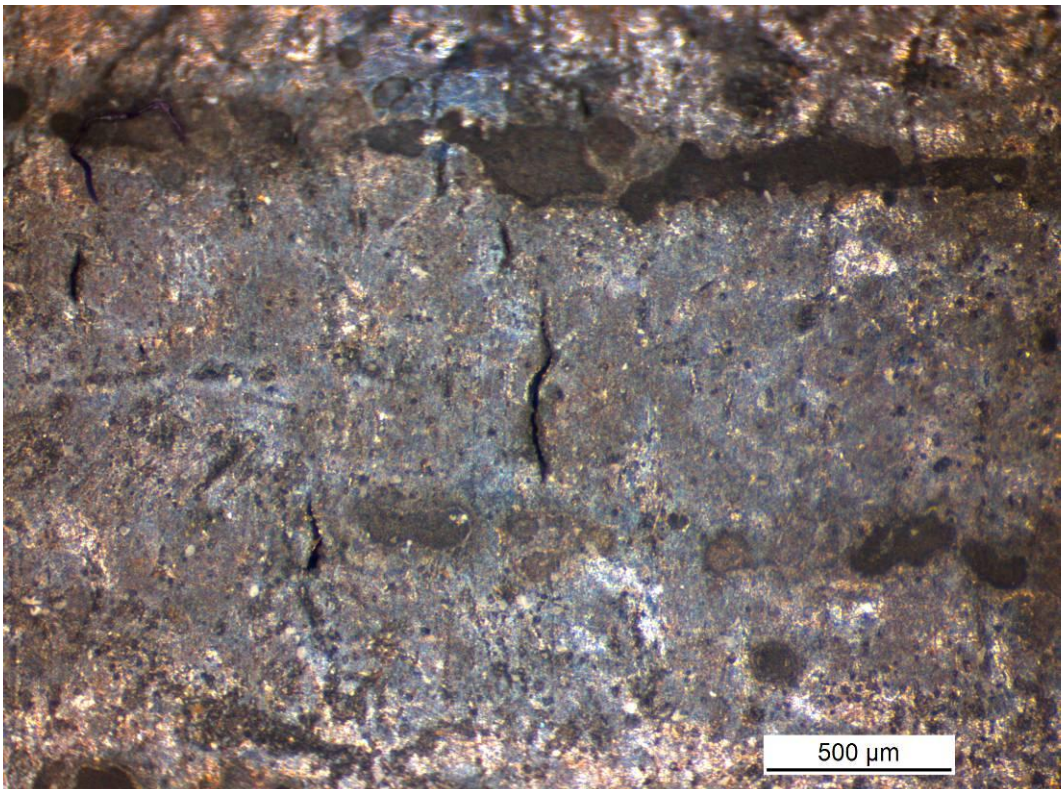


Fig. 2. Surface cracks in the uniaxial specimen V1 after 75 134 h at 150°C.

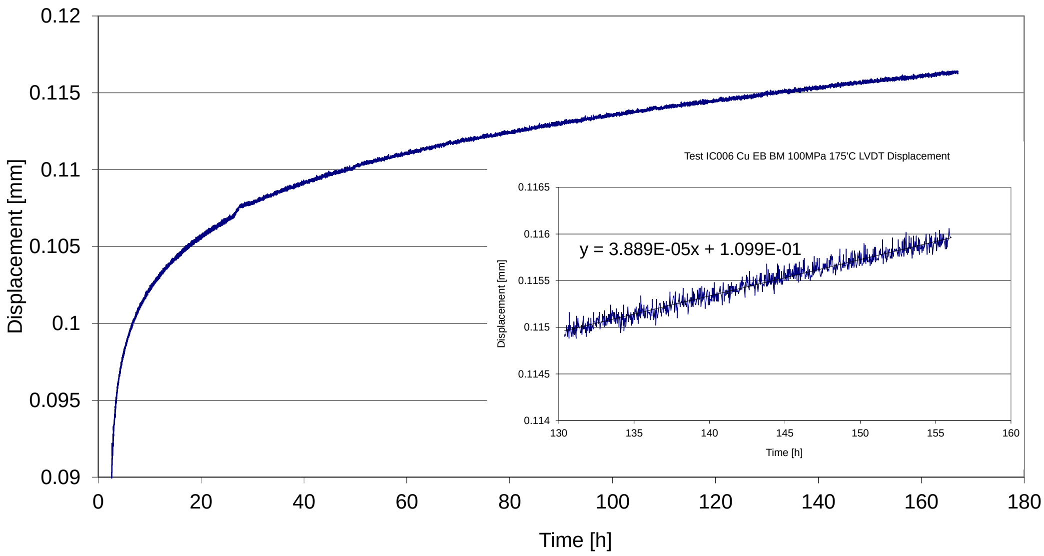


Fig. 3. Displacement curve of an impression creep test for Cu-OFP base material and determination of displacement rate by linear regression (insert)

3.2 Multiaxial testing

The specimen CS3 (Cu-OFP) 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 seven testing cycles (5000 h each, currently up to 35 000 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. The next interruption for inspection at 40 000 h will take place in May 2012.

After 15 000 h of exposure, the joint faces ("crack mouth") had opened by about 0.03 mm for near zero crack growth. After 25 000 h of exposure the joint tip has opened about 0.13 mm, indicating local deformation at the notch tip. Although the opening was measured at a different location it is obvious that the opening process is now accelerating.

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 all tests the cracks had a clearly brittle appearance, reflecting low ductility.

Because PD measurement was not applied in this series, the crack growth versus time calibration was determined from a series of interrupted tests at $K_I = 8.25$ MPa√m (tests CT2, 4, 5), as shown in Fig. 4. The test CT4 was interrupted at 3000 h and the test CT5 was interrupted at 980 h. These three tests followed the same trend in the load line displacement graph, Fig. 5, with the curve of CT5 running on top of the curve of CT2 and the curve of CT4 running slightly below. The results of the interrupted test series in Fig. 4 suggest that there is no incubation time and that crack extension is a linear function of time. Using this assumption the time to 0.5 mm crack growth was determined for each test. The longest completed test at $K_I = 6$ MPa√m, tested up to 14 733 h has shown low ductility and same type of brittle creep cracking as reported earlier [13], see also Fig. 25. Metallographic examination (Fig. 26) confirmed that the brittle intergranular cracking mechanism was by initiation, growth and coalescence of grain boundary cavities. Also, twinning deformation is seen in Fig. 26. A new test CT7 at intermediate load of $K_I = 8.25$ MPa√m is currently running at 2600 h.

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]	t 0.5mm
CT1	y294	8.973	5000	52	1029.7	0.3959	9.96	51.7
CT2	y299	8.25	4615.7	47.8	6198.2	0.559	8.71	355.8
CT4	y312	8.25	4576.6	47.8	3000	0.3052	5.53	271.2
CT5	y314	8.25	4634.2	47.8	980	0.235	1.47	333.3
CT3	y311	7.75	4350.6	44.9	8334.2	0.4944	4.17	999.3
CT7	y353	7	4046.9	39.9	2600	running		
CT6	y326	6	3354.3	34.8	14733	0.3809	4.37	1685.7

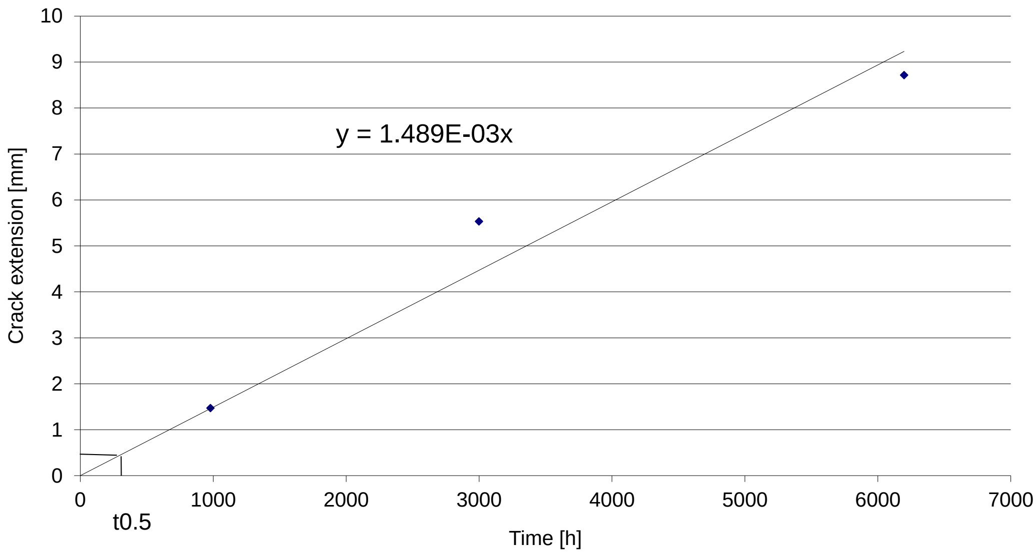


Fig. 4. The calibration curve for crack extension vs. testing time at K_I = 8.25 MPa √m at 175°C for Cu-OFHC (CT)

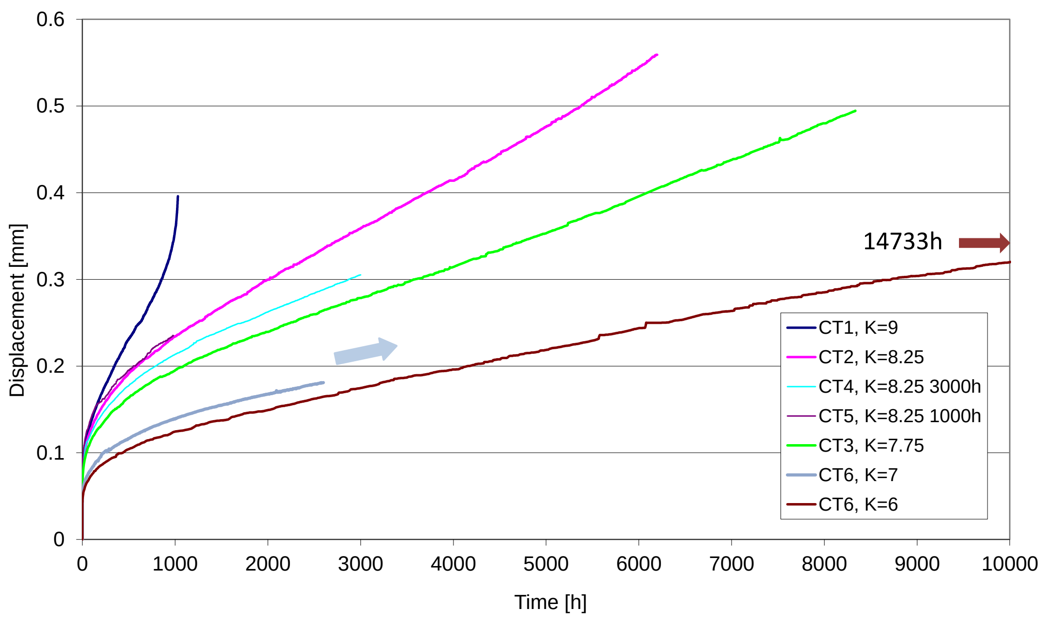


Fig. 5. Load line displacement of the Cu-OFHC CT-specimen test series at 175°C. The test CT6 is ongoing.

When the current four test results for OFHC copper at 175°C are plotted in terms of time to 0.5 mm crack growth the results already demonstrate the strong life shortening effect by multiaxiality (LICON effect), see Fig. 6. The data points (dark squares) at the three highest levels of loading (stress intensity factor K) run parallel to the uniaxial data line (not shown), which means that at high load levels there is no life shortening effect by multiaxiality. However, the test point at the lowest load level (open square) strongly deviates from the upper trend line. The data points are still too few for final conclusions, but if a "break-away" line is drawn through the two last data points the resulting slope of the trend line deviates from the upper trend line by a factor of ten. The corresponding life shortening factor at the lowest loading level (6 MPa√m) is about two orders of magnitude, and would increase further with reduced load. It is important to note that the life shortening effect by multiaxiality only exists in long term and at low loading levels.

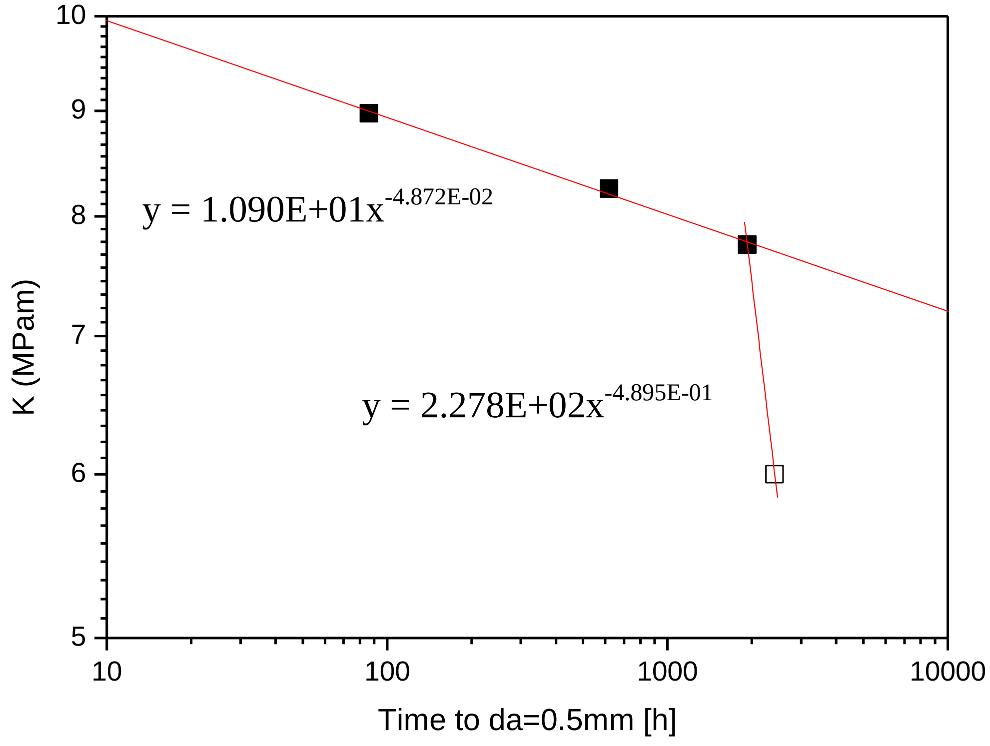
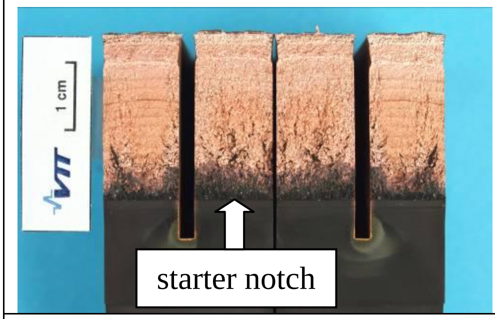


Fig. 6. Time to 0.5 mm crack growth for four Cu-OFHC CT specimens at 175°C.

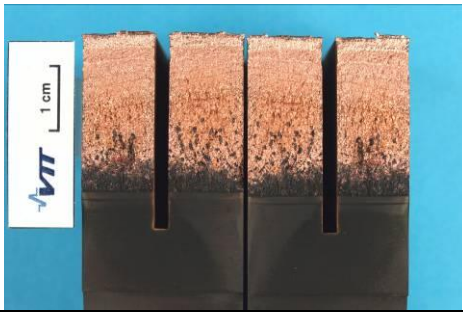
After creep crack initiation and growth testing of the Cu-OFHC material, a slice was removed from the centre of the specimen by wire erosion for metallography. After that the CT specimens were opened by high-cycle fatigue. At that point it was observed that all specimens showed oxidised spots on the fracture surfaces. The fracture surfaces are shown in Fig. 7, with crack growth direction upwards. On top of the horizontal starter notch line produced by wire erosion there is a completely oxidised area which represents the area of crack growth during the experiment. The crack propagation did not continue in one plane, because the crack branched very strongly as has been shown in Fig. 25. Therefore the area of continuous oxidation does not necessarily coincide with the crack extension (Δa) measured from the metallography slice, shown in Table 1. It is seen that there are oxidised grain boundaries on the fracture surfaces much further from the starter notch than the apparent crack extension (Δa).

The appearance of the fracture surfaces changes when the fatigue fracture mechanism changes from intergranular to transgranular, the change is clearest in specimen y314 (CT5). The results indicate that the grain boundaries of the OFHC base material have oxidised and the fatigue fracture follows the oxidised grain boundaries until the fracture mechanism changes to transgranular. The area of transgranular crack growth is seen as lighter area on top of each fracture surface. Somewhat comparable grain boundary oxidation has also been observed in the CT and uniaxial specimen tests in sulphide environments [10].

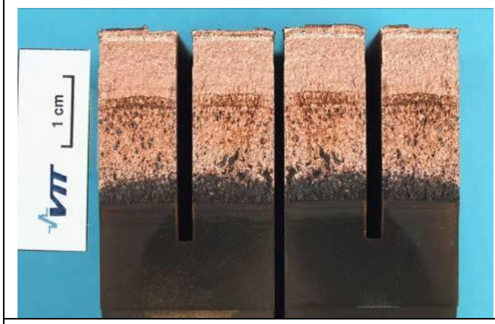
The dark areas on the fracture surface of specimen y314 (CT5) were analysed in SEM. In Fig. 8 the area analysed is shown in the top left figure. The analysis confirms that the dark areas on the fracture surface are copper oxide. The latest experiments suggest that the oxidation is most probably due to friction and heating of opposite fracture surfaces rubbing against each other during fatigue.



a) y311 (CT3) 7.75 MPa√m, Δa = 4.17 mm



b) y312 (CT4) 8.25 MPa√m, Δa = 5.53 mm



c) y314 (CT5) 8.25 MPa√m, Δa = 1.47 mm

d) y326 (CT6) 6 MPa√m, Δa = 4.37 mm

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

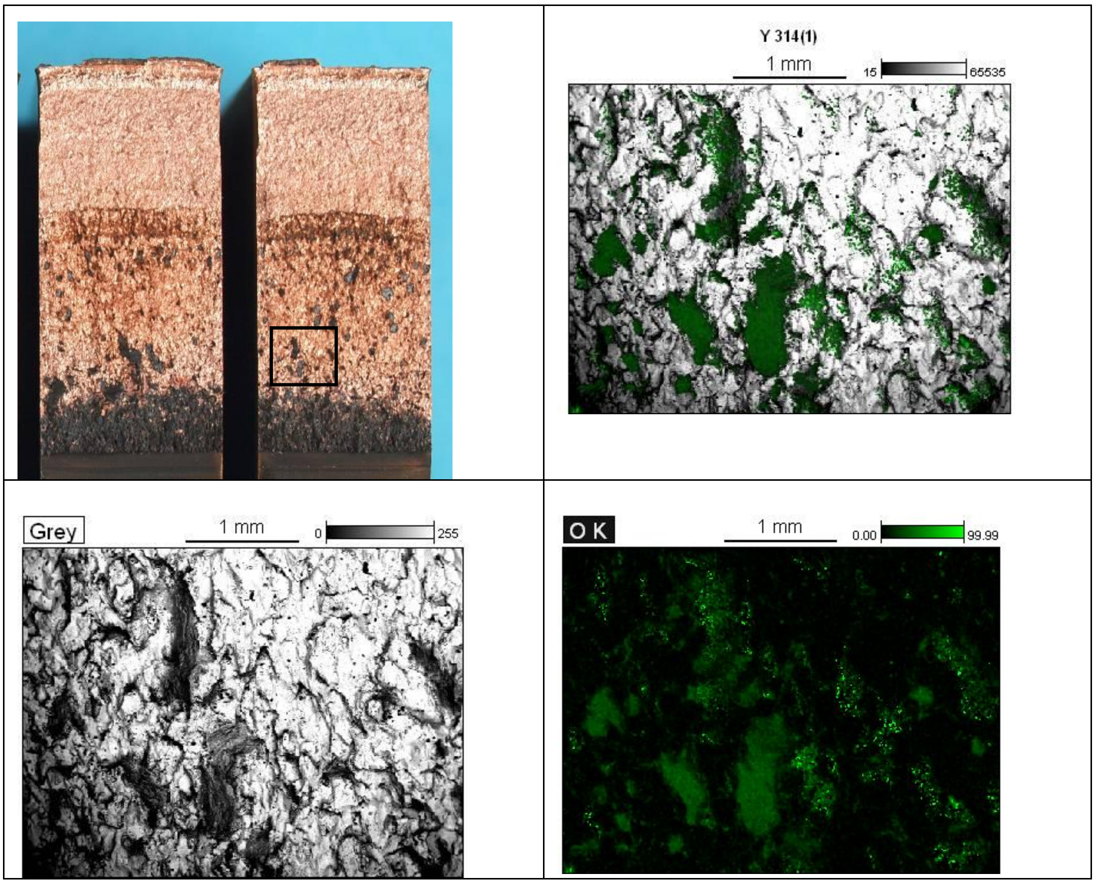


Fig. 8. EDS analysis of the oxidised areas of specimen y314 (CT5). Top left: area of the three analysis images indicated with a square. Bottom left: normal SEM image. Bottom right: Oxygen map. Top right: bottom left and right pictures superimposed.

A test series for comparison of creep behaviour of FSW and EB welded CT specimens has been started at identical conditions of K_I = 10 MPa√m at 175°C. The starter notch in both specimens is the natural notch. The comparison of load line displacement (LLD) curves is shown in Fig. 9 and the corresponding LLD rates in Fig. 10. Fig. 9 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 behaviour of the EB welded CT specimen is in line with that of uniaxial EB welded specimens which also tend to show higher initial strain and higher creep rates in comparison with FSW specimens.

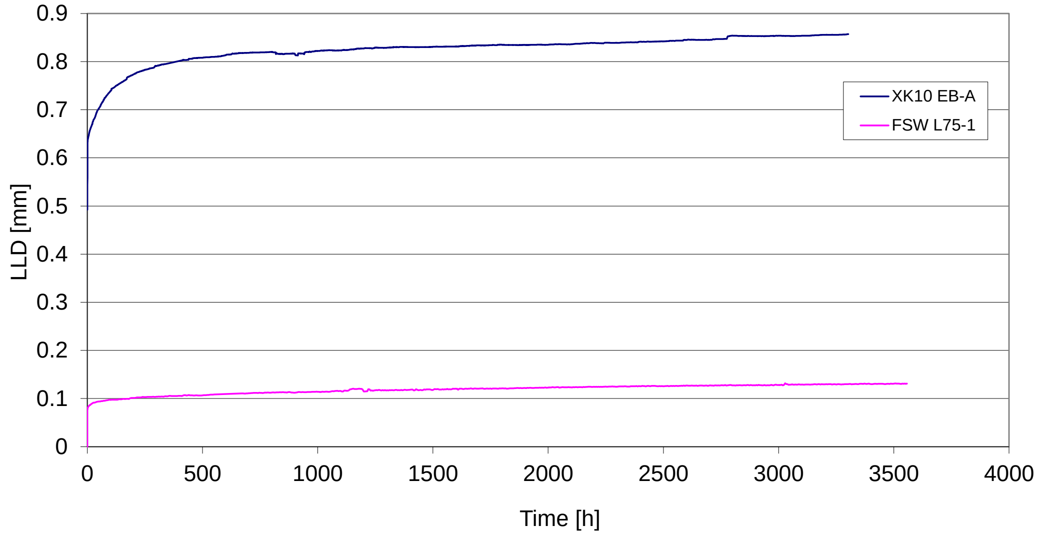


Fig. 9. Comparison of load line displacement curves of FSW and EB welded CT specimens at 175°C at 10 MPa√m

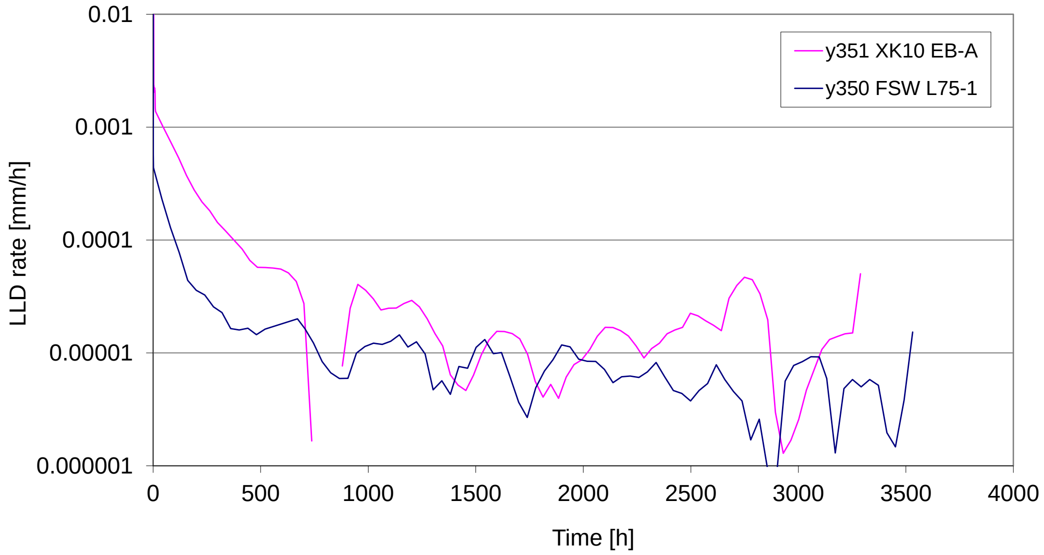


Fig. 10. Comparison of load line displacement rate of FSW and EB welded CT specimens at 175°C at 10 MPa√m

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. 11, again demonstrating the higher initial LLD and higher creep rate in the EB welded specimen.

The notched bar (NB) testing series has been delayed because the intention was to machine the cylindrical specimens with a circumferential notch (Fig. 12) using wire erosion in such a way that the specimen would rotate under water and the notch would be introduced by simply cutting with the wire to the desired depth. In this way deformation of the ligament can be avoided completely and very sharp notches can be introduced, much sharper than by turning in a lathe. The bending would normally deform the material at the notch tip and reduce the ductility and shorten the creep life. To our knowledge this way of machining the NB test specimens has not been used elsewhere and can be of interest world-wide.

Construction of the rotating device has, however, been a technical challenge and therefore has proved to be rather time consuming at the subcontractor's workshop. The equipment is expected to be operable in March 2012. The NB test results will be used to demonstrate the effect of multiaxility on lifetime of copper.

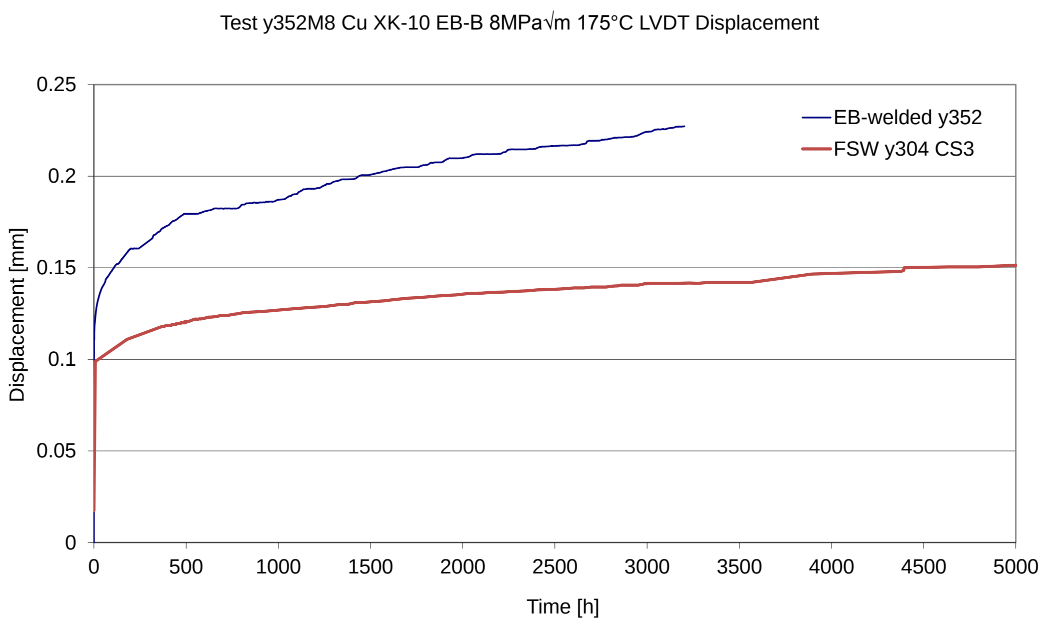


Fig. 11. Comparison of load line displacement curves of FSW and EB welded CT specimens at 175°C / 8 MPa√m

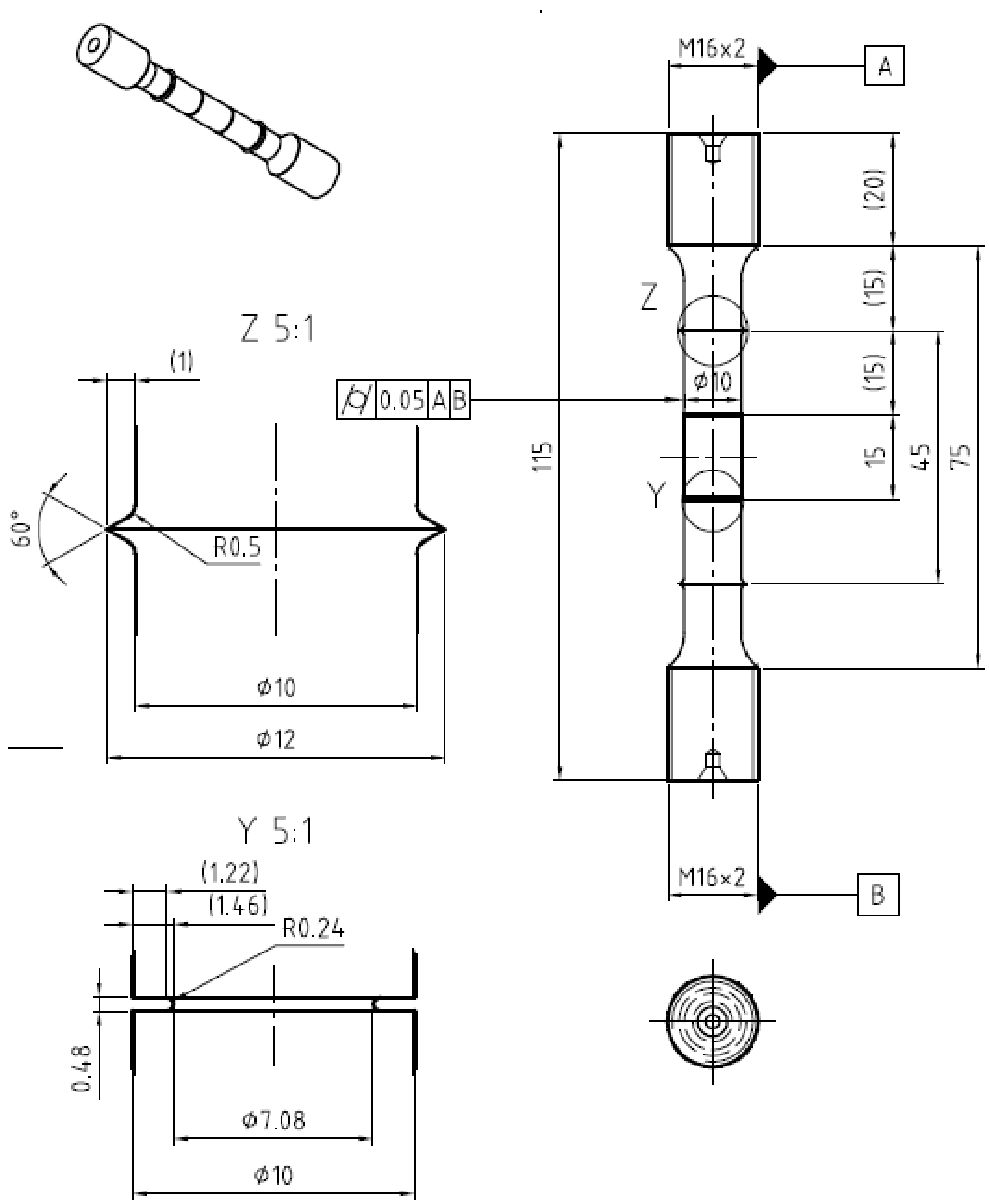


Fig. 12. Notched bar specimen with double notch with root radius R = 0.24 mm, detail Y at the bottom showing the circumferential notch geometry to be introduced by wire erosion

3.3 Combined creep and corrosion (CT) testing

For combined creep and corrosion testing of OFP copper, 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 displacement (LLD). The specimen is inserted to a Teflon jar where the simulated Olkiluoto groundwater (aerated) is circulated at a temperature of 90°C. The glass jar used earlier was replaced by a Teflon jar as in the previous experiment the glass vessel had eroded. The pins used for loading the specimen were made of pre-oxidised zirconium to avoid galvanic corrosion.

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

The third combined corrosion and creep test was started at a plane stress reference stress of 55 MPa with a FSW welded CT specimen L75-2 with a wire eroded starter notch in order to allow transport of saline water into the notch root area. EDM machining with wire thickness of 0.1 mm resulted in a notch width of 0.165 mm. The notch tip was aimed at the processing line of the FSW joint, corresponding to the fusion line of a usual metal weld, see Fig. 13.

After the 5000 h test the specimen had clearly corroded (Fig. 14), although much less than the previous specimen [13]. Pitting corrosion was observed on the outer surface with some recrystallized copper crystals (Figs. 15-16). Crystallization of copper in the corrosion pits is a result of water being oversaturated with copper. Changing the pin material to oxidised zirconium has much reduced the general corrosion on the outer surface, but there is still a possibility of galvanic corrosion in the test loop due to metallic materials further away from the test specimen. Therefore, the next test is suggested to be conducted without mechanical loading under aerated conditions but with excluded possibility of galvanic corrosion.

The load line displacement of the specimen L75-2 was compared against the displacement of an identical test L75-3 in air. The two displacement curves are rather similar, as shown in Fig. 17. The slightly smaller displacement in the saline test than that of the reference test in air was not expected, but it is possible that oxidation between the specimen and the transducer in the saline test has reduced the measured displacement. The metallographic inspection of the notch root did not show any crack extension, corrosion damage or crack opening, see Fig. 18 (right). The results suggest that the saline environment did not accelerate creep at the notch tip and that there is no combined mechanism of creep and corrosion occurring in copper in aerated saline environment.

There was some corrosion damage about 3.75 mm to the left from the notch tip in Fig. 18 (left). Fig. 18 also shows that the natural notch was slightly longer than the wire eroded notch although the intention was to extend the wire eroded notch beyond the natural one. Fig. 19 shows the notch tip region of the reference specimen FSW L75-3, and also “banding” in the FSW weld metal. However, this banding goes through the grains and is thus not banding produced by layers of small and large grains as reported in [11].

The inspection of the fracture surface after breaking the specimen open by fatigue loading did not show similar oxidation of the grain boundaries as was observed in

Cu-OFHC specimens (cf. Figs. 7-8). In Fig. 20 the fracture surface looks rather clean, but a closer look (Fig. 21) revealed oxidised grain boundaries perpendicular to the crack plane. The research on FSW welded copper at Aalto University has shown oxide particles near the processing line, but not on grain boundaries [12]. This unexpected issue needs further clarification.

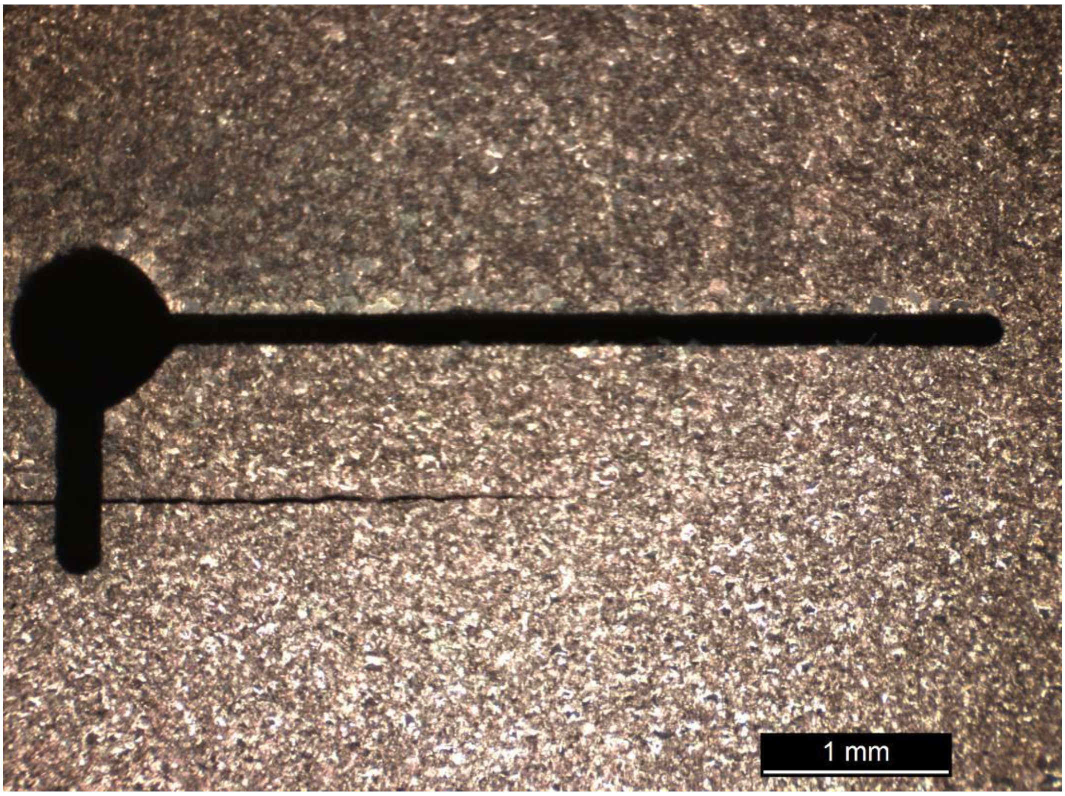


Fig. 13. The wire eroded starter notch in the specimen FSW L75-2. The natural crack is seen below the EDM notch.

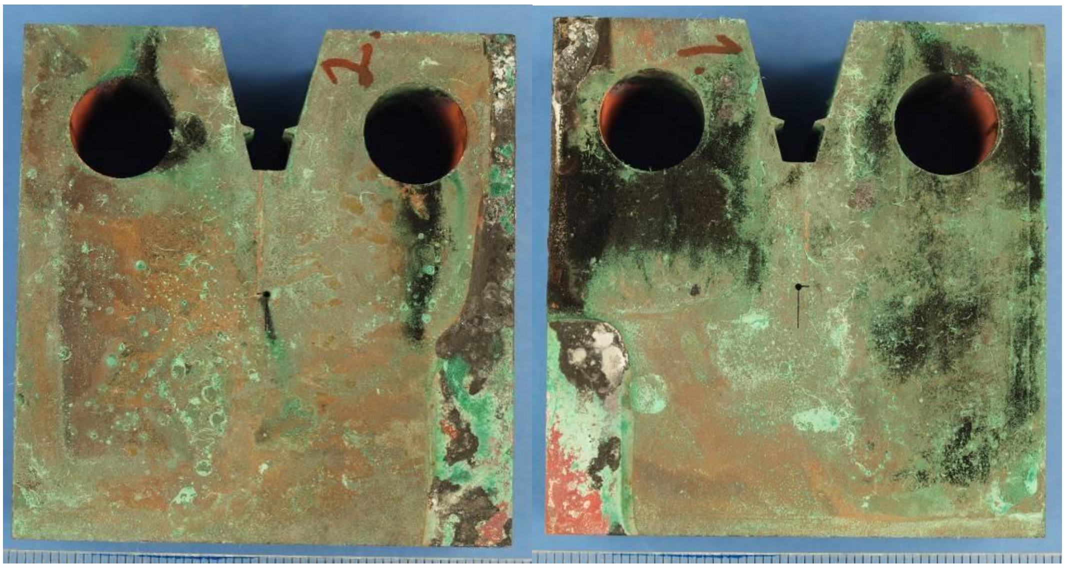


Fig. 14. The outer surface of the specimen FSW L75-2 after the corrosion experiment in saline water at a plane stress reference stress of 55 MPa at 90°C

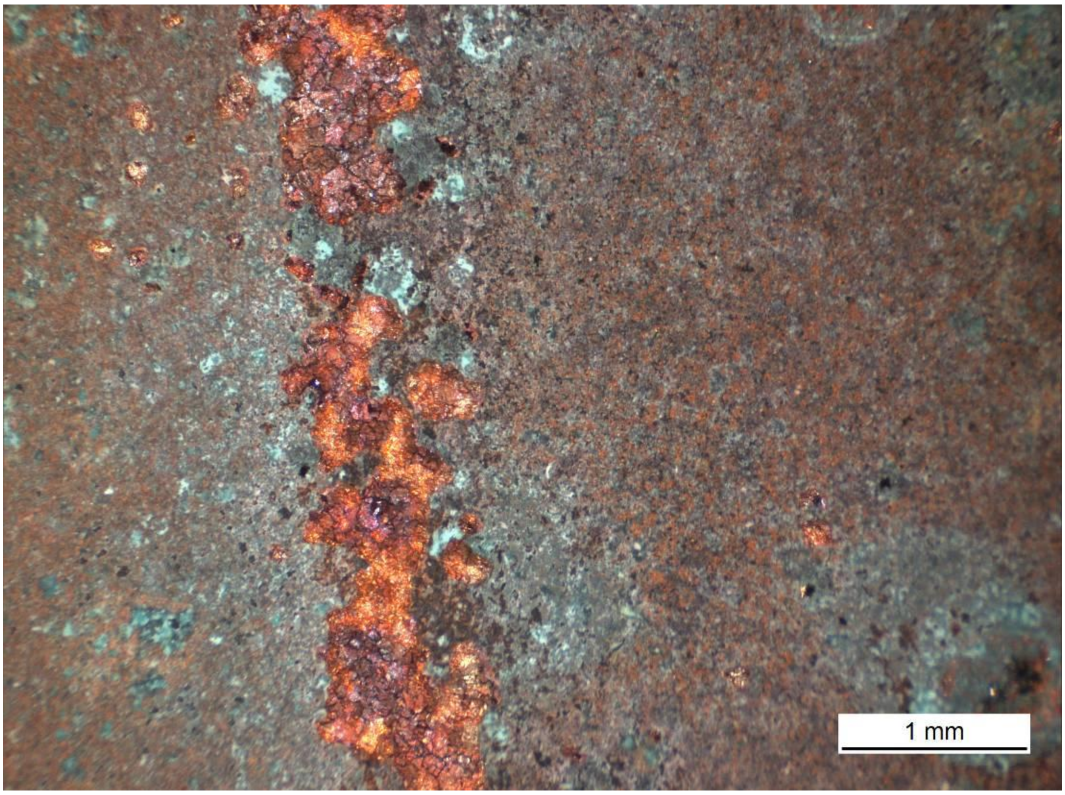


Fig. 15. Pitting corrosion on the outer surface of the specimen FSW L75-2 after the corrosion experiment in saline water at 90°C

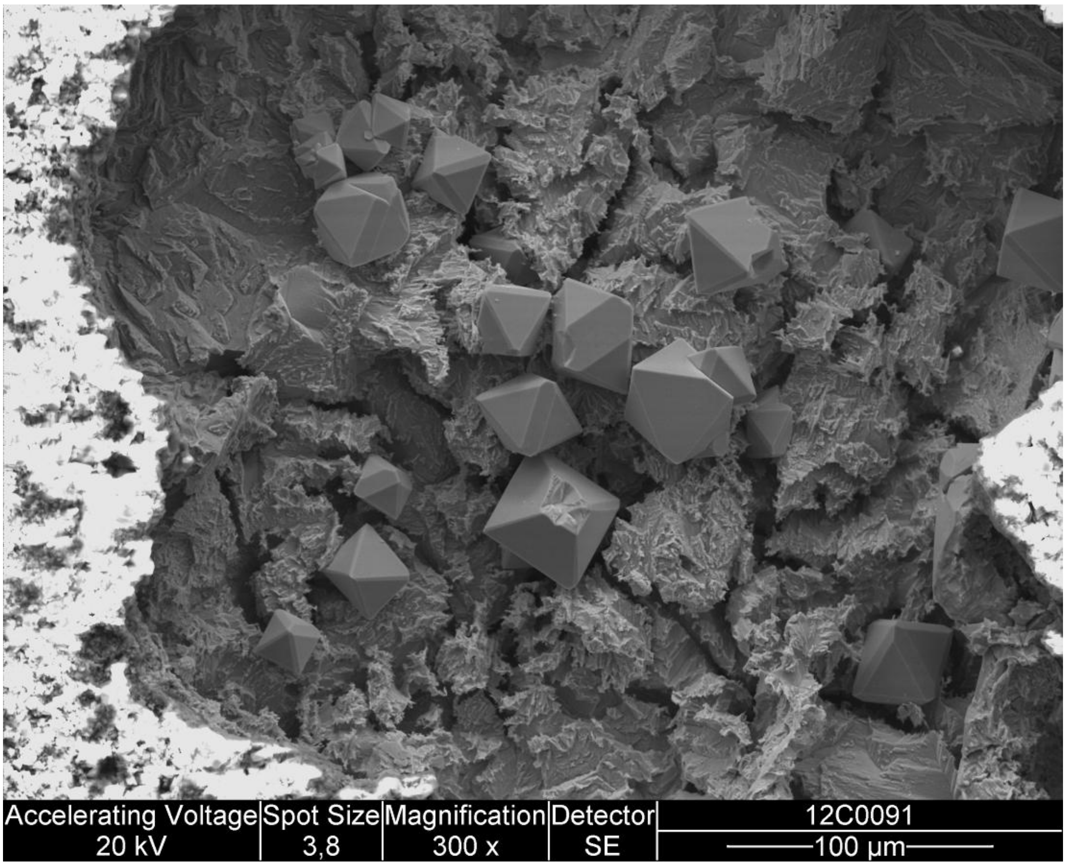


Fig. 16. Pitting corrosion and recrystallized copper on the outer surface of the specimen FSW L75-2 after the corrosion experiment in saline water at 90°C

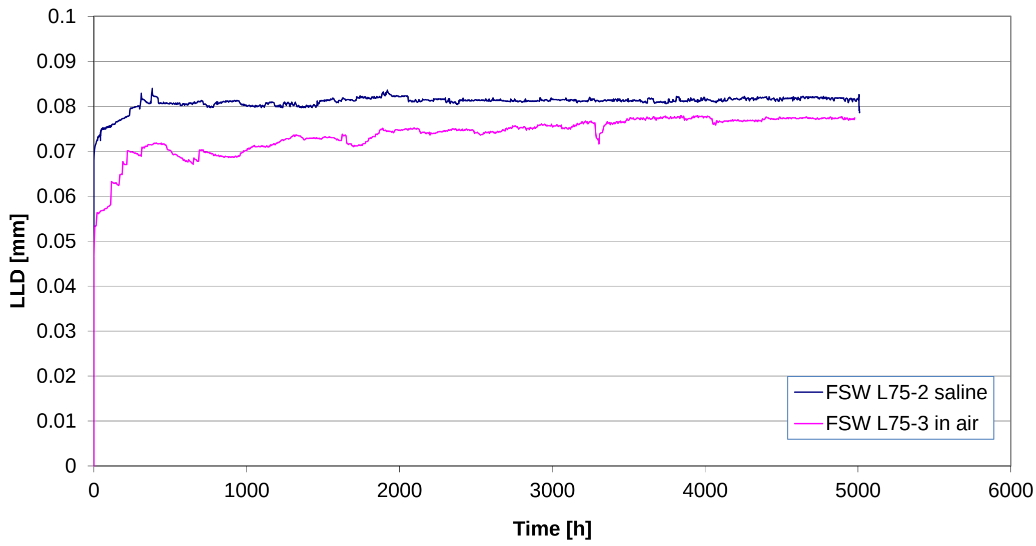


Fig. 17. Load line displacement of two FSW CT specimens at 55 MPa reference stress at 90°C: upper curve in saline water and lower curve from a reference test in air.

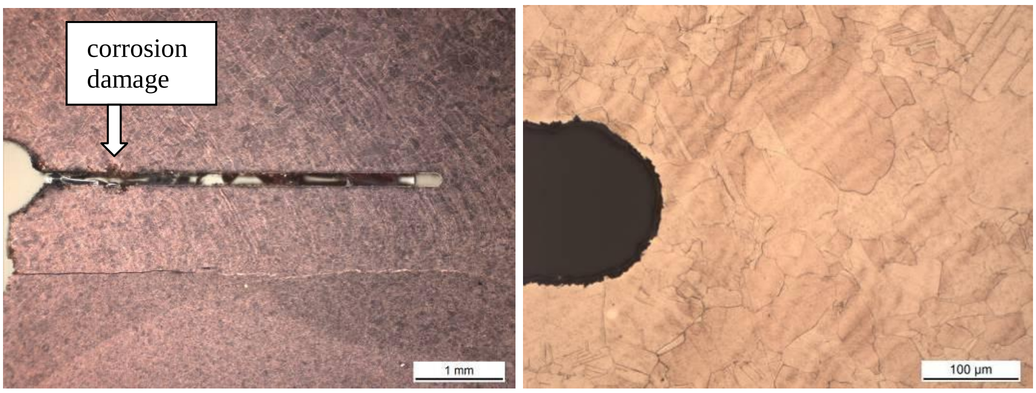


Fig. 18. The wire eroded notch in specimen FSW L75-2 after the experiment and the natural notch below (left figure) and a detail from the notch tip (right)

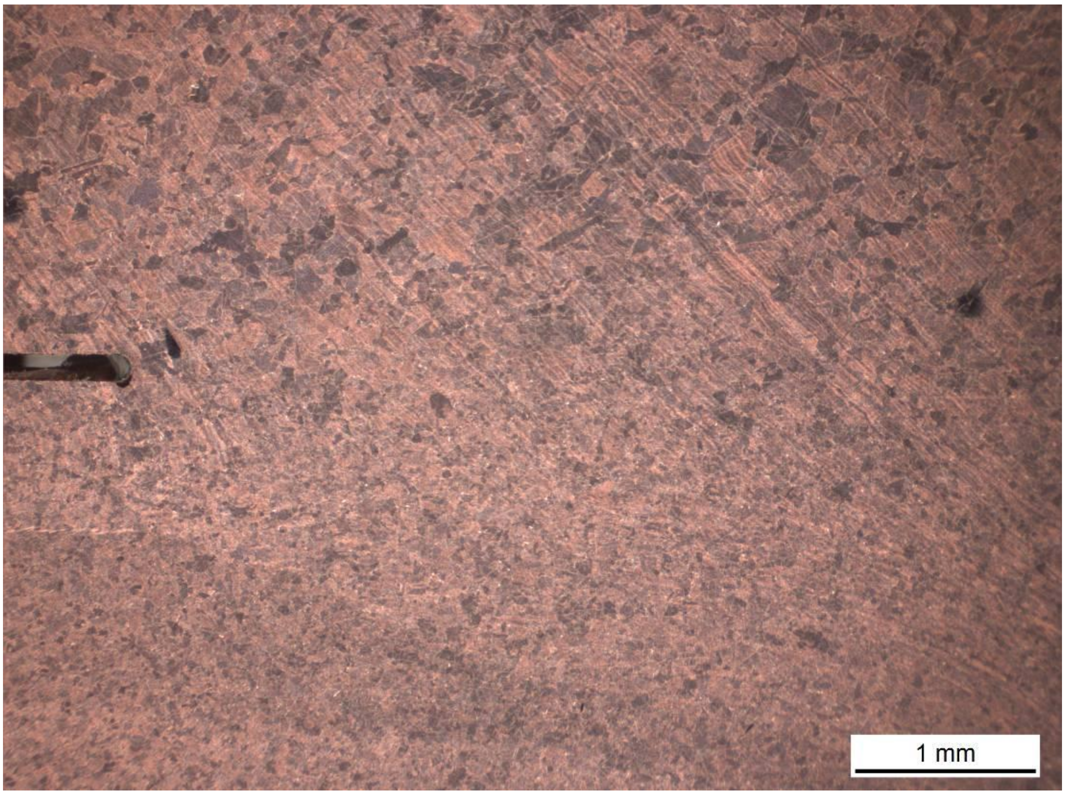


Fig. 19. The notch root region of the reference specimen FSW L75-3 tested in air at 55 MPa reference stress at 90°C; note also banding in the weld microstructure. Natural notch is below the EDM notch.

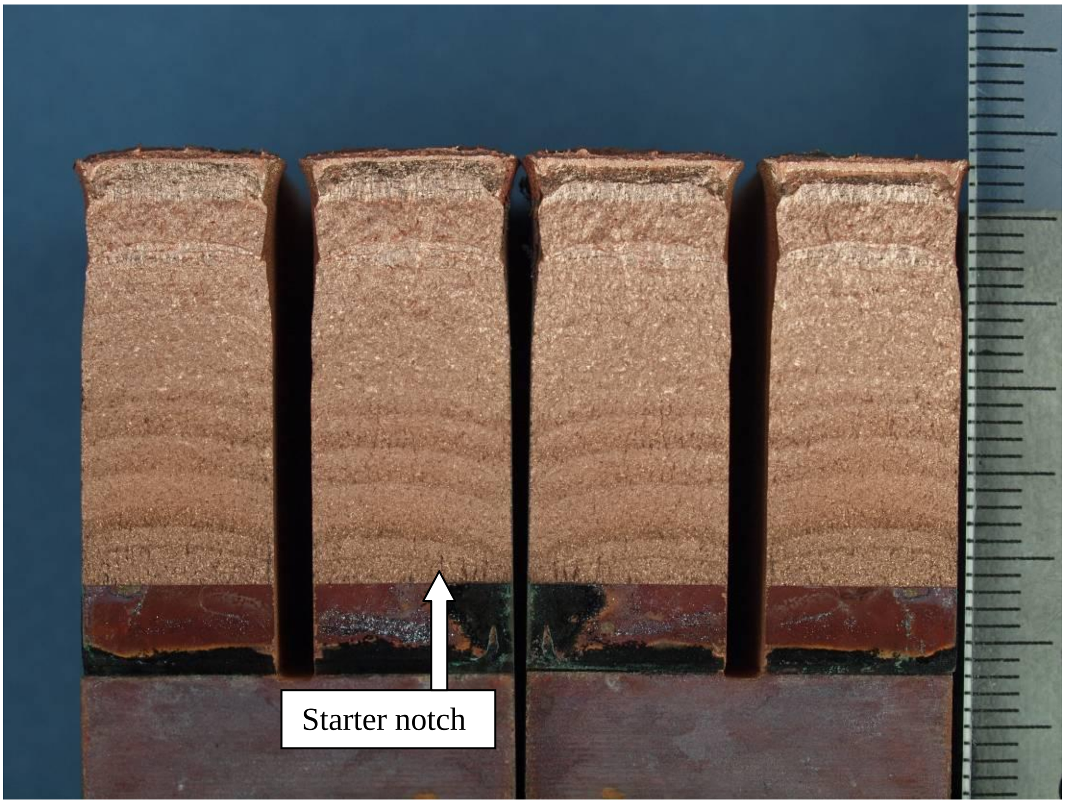


Fig. 20. Fracture surface of the specimen FSW L75-2 after 5000 h in saline water at 90°C and 55 MPa reference stress.

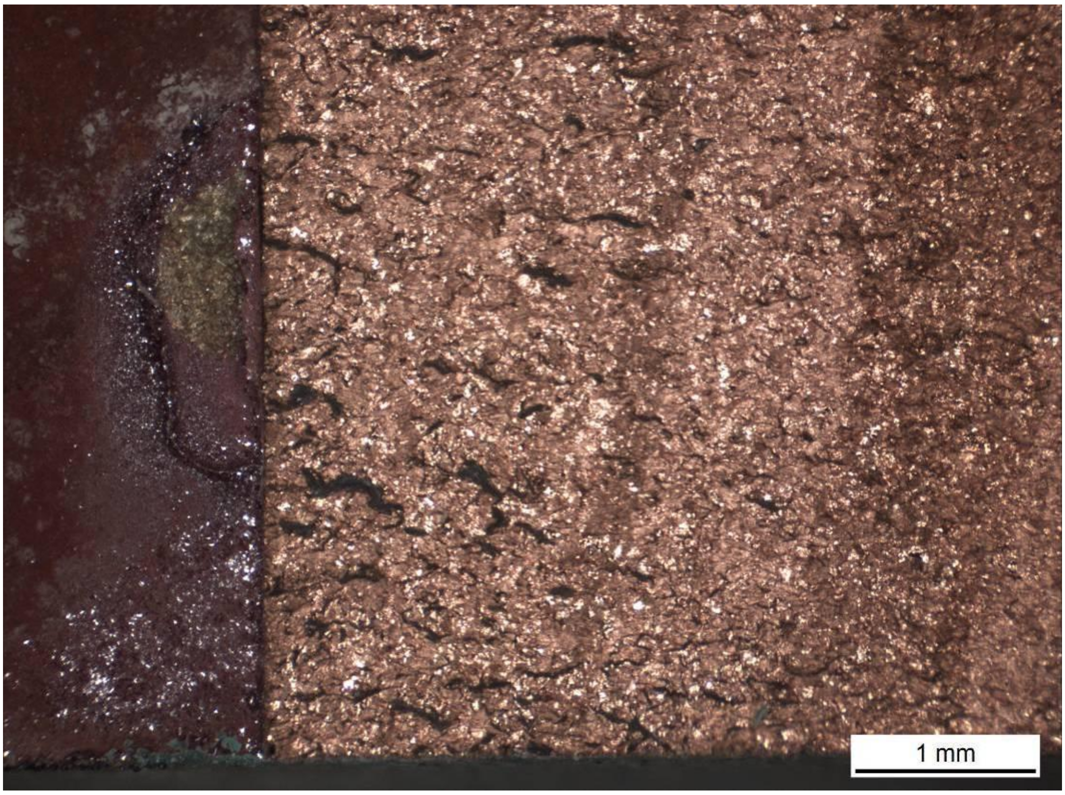


Fig. 21. Detail of Fig. 20 with oxidation on surfaces perpendicular to the crack plane. Direction of crack growth from left to right.

3.4 Metallography

Cu-OFP

The OFP copper CT-specimen (CS3) with a friction stir weld, tested at 175°C at 35 MPa reference stress with interruptions and optical and scanning electron (EBSD) microscopy every 5000 h, is currently running at 38 000 h. The latest inspection has taken place at 35 000 h. Grain boundary cavities near the notch tip observed in the latest inspection are shown in Fig 22 and the tip of the natural crack with joint line hooking is shown in Fig. 23. The cavity density, as evaluated at each inspection of the CT specimen, is shown as a function of testing time in Fig. 24. 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 any observed cavity coalescence or clear orientated formation up to 35 000 h. The last inspection showed a lower cavity density than at 30 000 h. This may be due to the sensitivity of the measured cavity density to the specimen preparation and etching process.

As expected, the cavity density was found to increase towards the notch tip. The cavity density decreases quickly beyond a distance of 0.75 mm from the notch tip. The area with observed cavities extended to some 1.2 mm ahead of the crack tip. The cavities are associated with minimal deformation in the matrix as reported earlier [13].

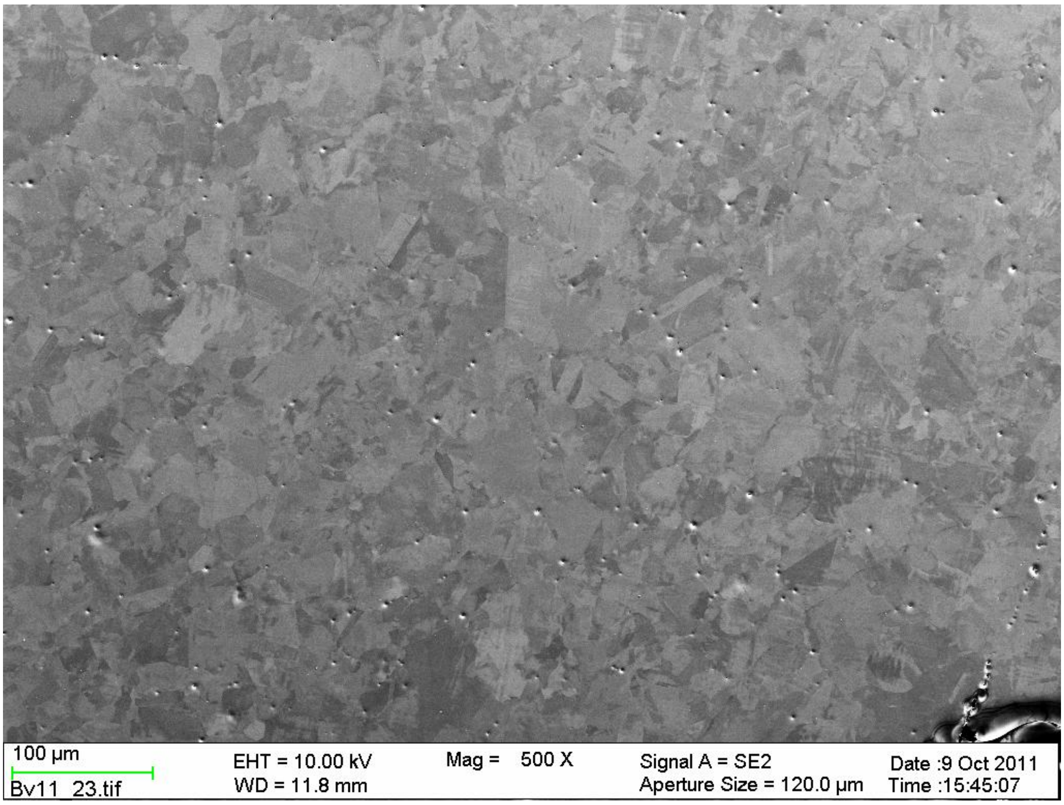


Fig. 22. Cavities at the notch tip of the specimen CS3 after 35 000 h of testing

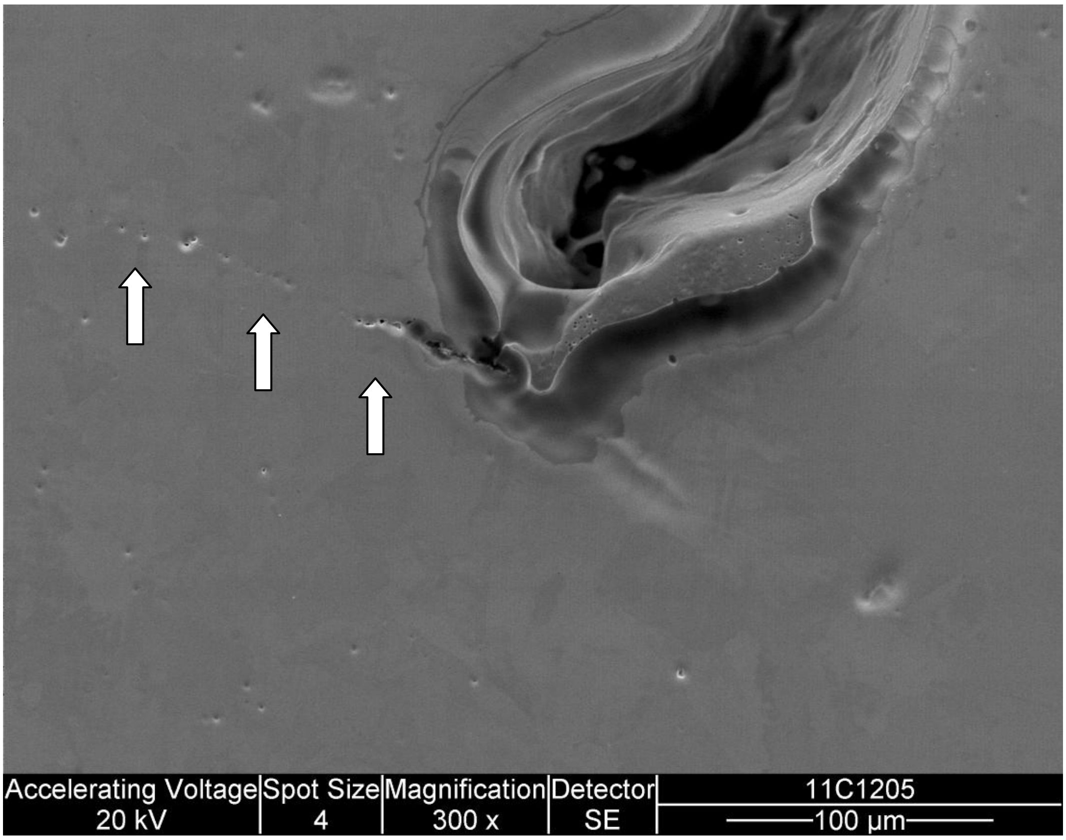


Fig. 23. Notch tip of the specimen CS3 after 35 000 h of testing, notch direction vertical, loading direction horizontal, and joint line hooking indicated with arrows

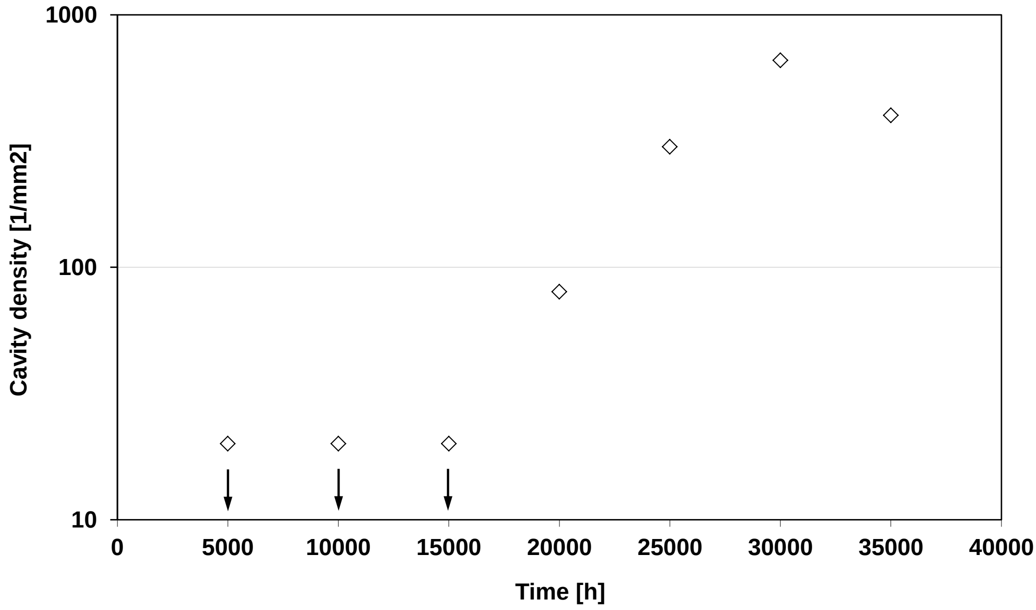


Fig 24. Cavity density in the OFP copper CT-specimen CS3 with friction stir weld at 175°C at 35 MPa reference stress; up to 15 000 h the cavity size was below the limit of detection.

Cu-OFHC

A series of Cu-OFHC CT specimens has been tested in air at 175°C. The test matrix is shown in Table 1 and the test details are given in chapter 3.2. The longest completed test (CT6) at K_I = 6 MPa√m, tested up to 14 733 h has shown low ductility (Fig. 25), strong crack branching and similar brittle type of creep cracking as reported earlier [13]. Metallographic examination (Fig. 26) confirmed that the brittle intergranular cracking mechanism was by initiation, growth and coalescence of grain boundary cavities. Also, twinning deformation is seen in Fig. 26.

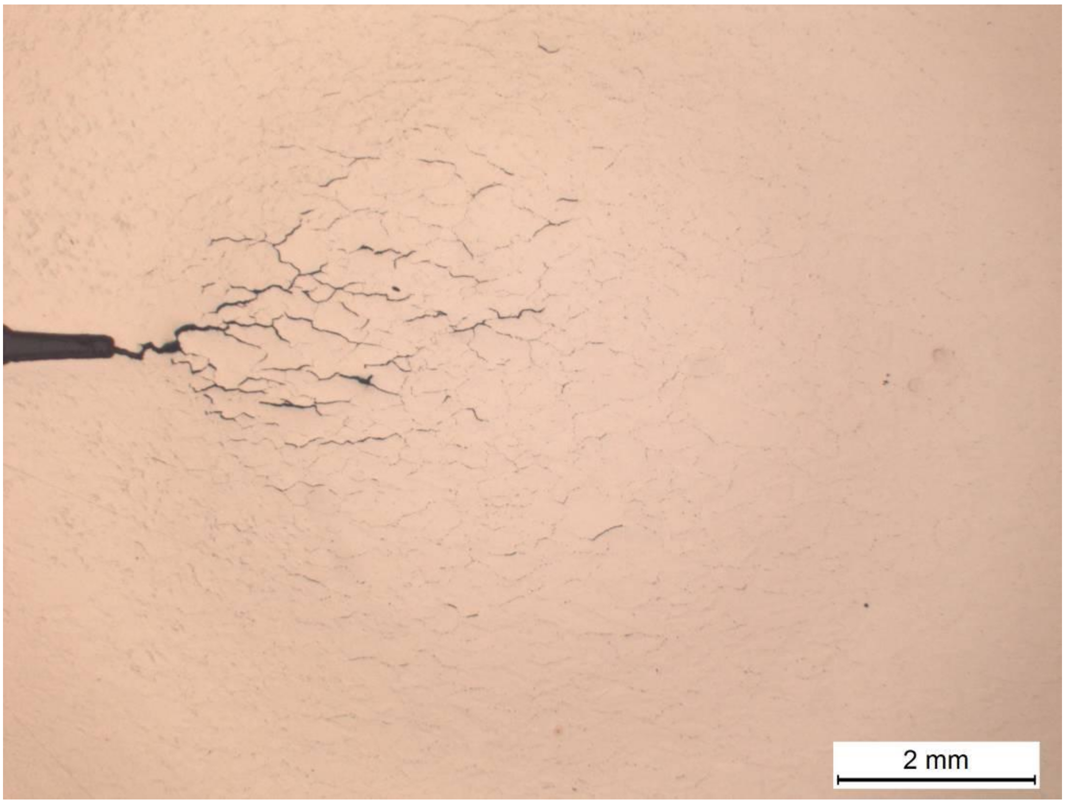


Fig 25. Crack branching in a Cu-OFHC specimen CT6 after 14 733 h of testing at 175°C, un-etched sample

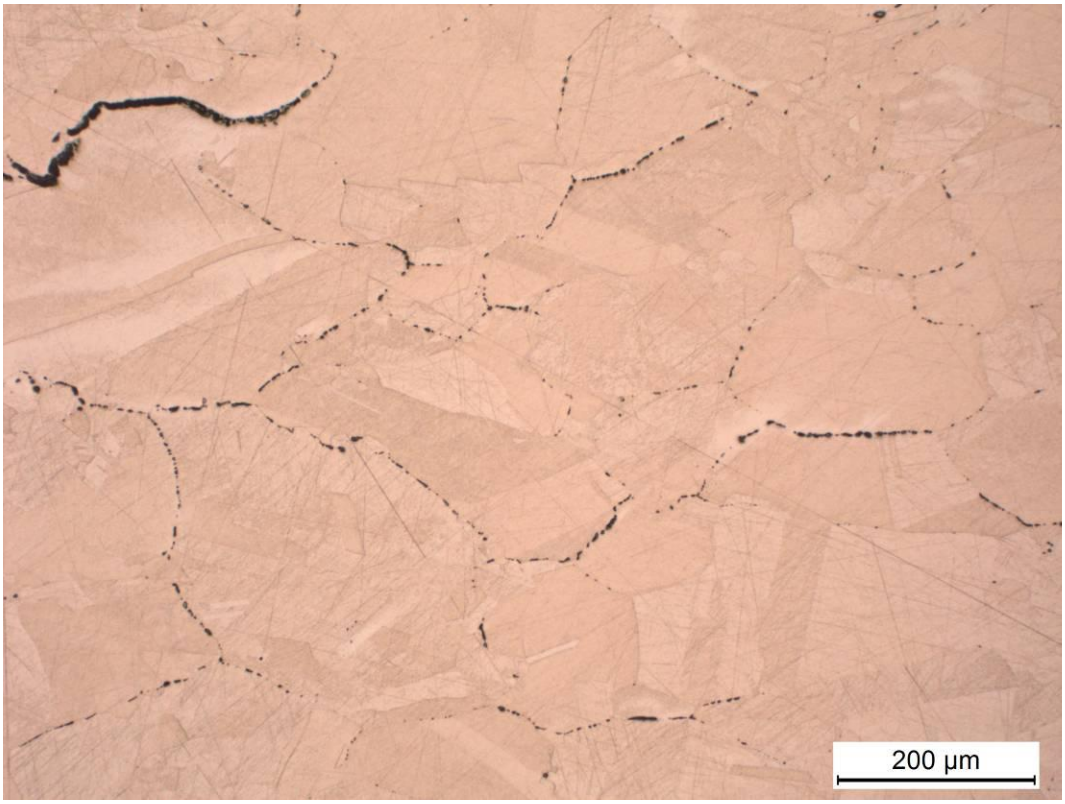


Fig 26. Creep cavitation at the grain boundaries next to the tip of the main crack in specimen CT6 of Fig. 25, etched sample

3.5 Creep modelling

The LCSP creep model [14] developed at VTT has been implemented and applied in FE analysis. Primary, secondary and tertiary creep terms are included in the model and analysis. The analysis of the copper overpack was started with two meshes, Fig. 27. In the general mesh (Fig. 27 left) there is a bigger gap between the cylinder and the lid than in the design specification [15]. This is done deliberately in order to study the stresses and strains in the case where the lower corner of the lid does not come into contact with the cylinder (Fig. 28). In the other mesh (Fig. 27 right) the gap is according to the specification. In that case the lid will creep into contact with the cylinder and the stress state will change especially around the inner corner of the lid. The von Mises stress distribution after 50 kh of creep under pressure of 14 MPa with the oversized gap is shown in Fig. 28 and the vertical equivalent strain distribution in Fig. 29. The analysis will continue in 2012 with special emphasis on the weld areas of the FSW and EB welded canisters and their lifetime.

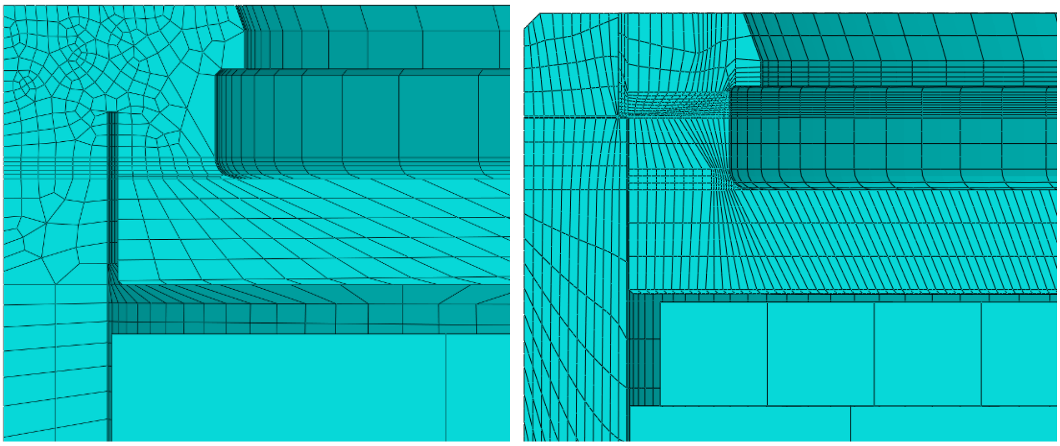


Fig. 27. A general FE mesh at the copper overpack lid corner area with an oversized gap (left) and a mesh for the EB welded canister (right)

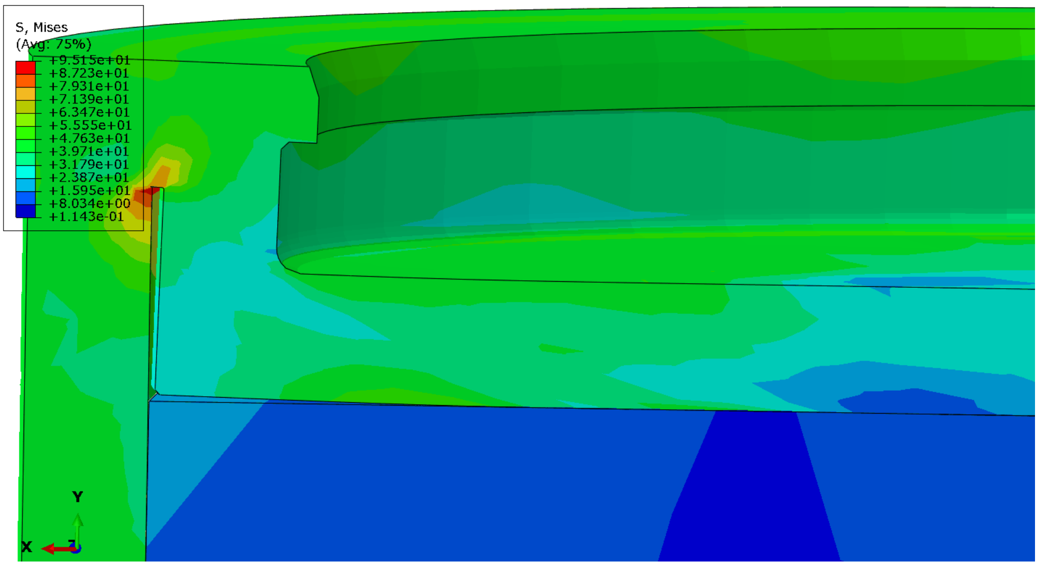


Fig. 28. Predicted von Mises stress distribution with an oversized gap between the lid and the cylinder with pressure 14 MPa after 50 kh.

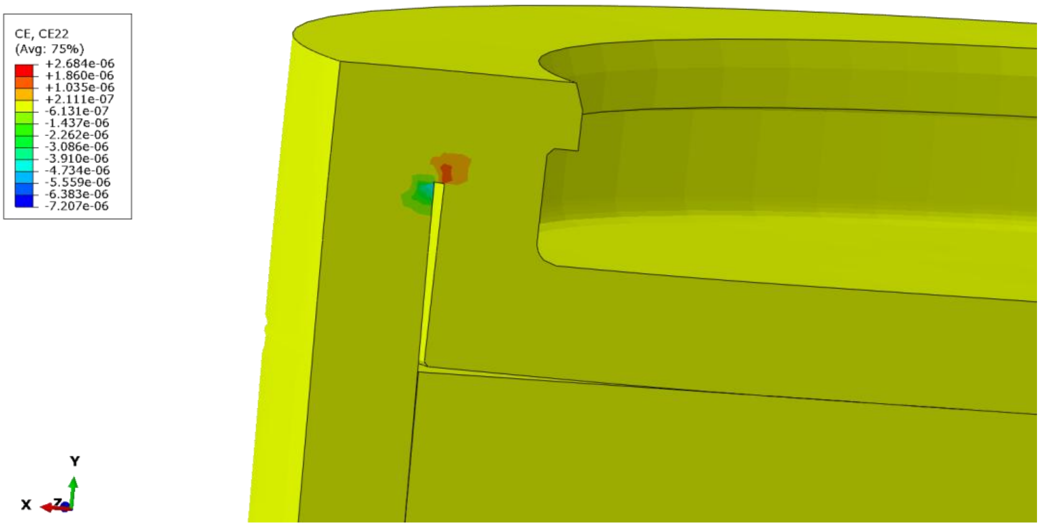


Fig. 29. Predicted equivalent strain distribution in y-direction (vertical) with pressure 14 MPa, 50 kh.

3.6 Optical strain measurement

The optical high temperature strain measurement system based on Speckle image analysis (SPICA), provided by KEMA in the Netherlands, was applied on the notch root area on the side surface of a CT specimen. With this method it is possible to measure 2D strain distribution on the test specimen. High resolution digital photographs are taken before and after the test, and with special software the movement of each pattern is followed to produce a strain distribution map. The method is best suited for continuous surfaces and therefore the analysis of the results required special efforts because of the missing information at the notch. The first trial suffered a bit from the microscope being slightly tilted when the first pictures were taken, which caused some false strain readings in the analysis and reduced the accuracy, but the method has proven to be applicable. An example of the strain analysis is shown in Fig. 30.

In the next stage the same experiment will be analysed by FE and the strain distributions predicted by FE can be compared against the measured ones. In this way SPICA can be used for verifying the FE strain predictions experimentally, a task which is generally not trivial. The SPICA method has been used in many other applications and is considered generally a reliable approach to measuring surface strain distributions.

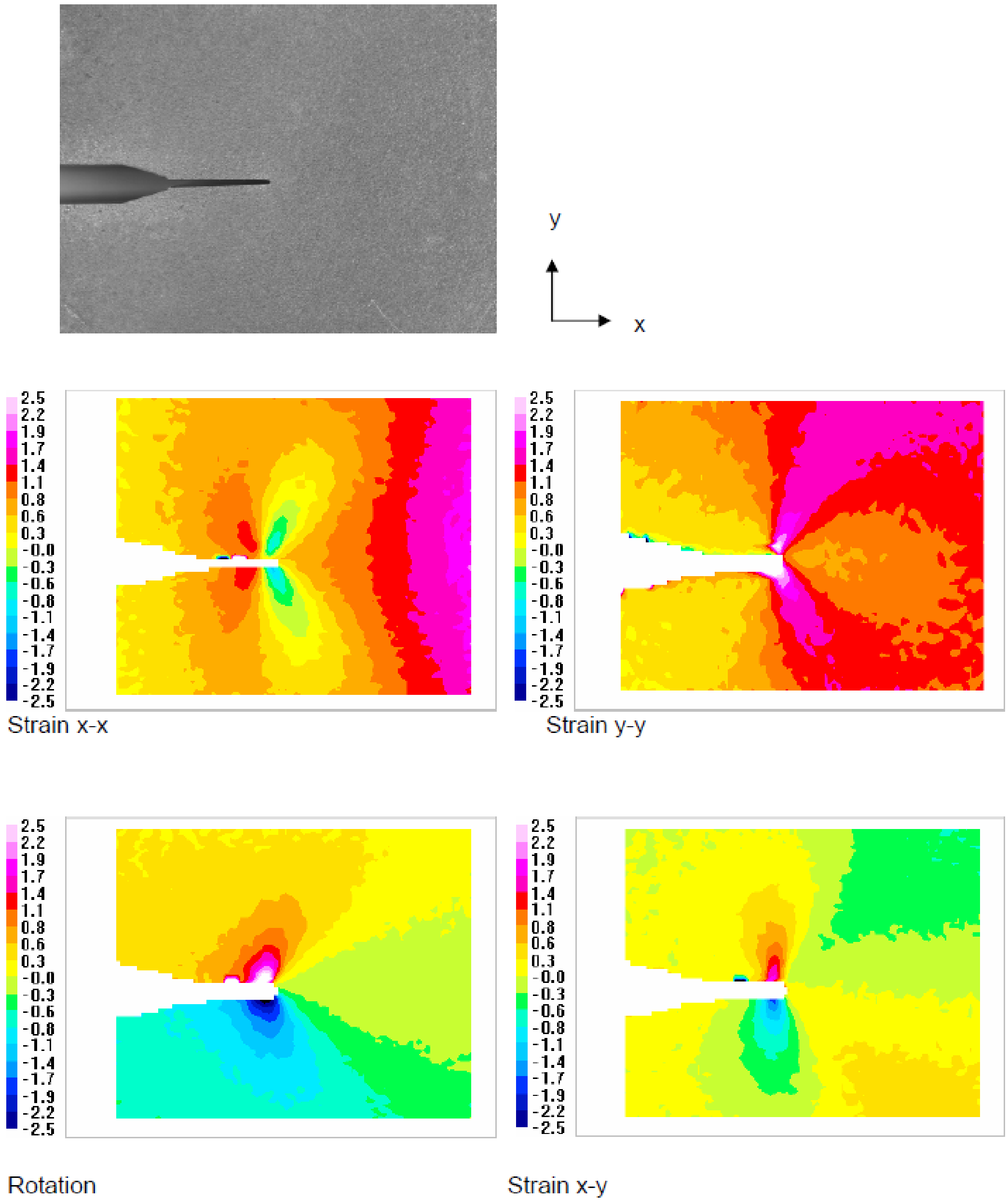


Fig. 30. The SPICA strain measurement results of a Cu-OFP CT specimen y331 tested for 1000 h at 126 MPa at 175°C

4 Publications

J. Rantala, J. Salonen, P. Auerkari, S. Holmström, Long-term integrity of copper overpack, Final Report, KYT2010 Finnish Research Programme on Nuclear Waste Management 2006-2010, Ministry of Employment and the Economy, 26/2011

The following paper was submitted and accepted for the conference in 2011, but the event was postponed to spring 2012 due to the tsunami in Japan:

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

The PhD of Juhani Rantala is on-going. The work deals with the effect of multiaxiality on creep damage initiation in copper and CMV steel.

5 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 35 000 h (4 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 83 200 h (9.5 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.

Change of loading pin material largely prevented the previously observed heavy general corrosion in the combined corrosion and creep testing of welded CT (OFP) specimens that were immersed in aerated simulated Olkiluoto groundwater at 90°C. However, some pitting corrosion was still found, probably due to galvanic corrosion that needs to be excluded.

Optican strain measurement system SPICA has been applied on CT specimens to measure strain distribution at the CT specimen notch tip.

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. Arilahti, E., Mattila, M., Lehtikuusi, T., Saario, T. and Varis, P., Sulphide-induced embrittlement of CuOFP– Intermediate Report 2. VTT Research Report VTT-R-00291-12, January, 2012
11. Savolainen K, Saukkonen T, Hänninen H, Banding in copper friction stir weld, Sci and Techn of Welding and joining, 2012, vol. 17, No 2, pp. 111-115.
12. Savolainen K, Friction Stir Welding of Copper and Microstructure and Properties of the Welds, Aalto University publication series Doctoral Dissertations 13/2012, Espoo, 170p.
13. J. Rantala, J. Salonen, P. Auerkari, S. Holmström, T. Saukkonen, Long-term integrity of copper overpack – Final report 2010, VTT Research Report VTT-R-01581-11, Espoo, 28p.
14. Holmström S. Engineering tools for robust creep modeling. Dissertation/VTT Publication 728 (2010). VTT, Espoo, 94 + 53 p.

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