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Experimentally verified model based predictions for integrity of Cu overpack

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Abstract

Behaviour of Cu-OFP has been modelled based on creep and relaxation test results in order to facilitate a full 3D creep FE analysis for the nuclear waste disposal canister with a cast iron insert and a copper overpack under external pressure. Stress history dependence of copper has been tested. The friction stir welding (FSW) process has been modified by changing the direction of rotation of the welding tool, which has eliminated the turn-back of joint line hooking. In order to reduce the amount of oxide particles the FSW process is now conducted in protective atmosphere. The behaviour of oxide particle layers in the old and new welds has been tested.

1. Introduction

Creep and relaxation properties of Cu-OFP have been tested experimentally within the Finnish Research Programme on Nuclear Waste Management (KYT) [1]. 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 (Figure 1). If a decision is to place the canisters closer to each other, the temperature will increase. The top temperature will depend also on the rate of wetting in individual disposal holes, which might vary a lot, depending on the flow of water in the bedrock. Therefore, it is possible, that at least some canisters will experience peak temperatures of 90 °C and above. The development of the swelling pressure in bentonite surrounding the canisters will also depend on the rate of wetting.

For the protective copper (Cu-OFP) overpack of the canister, creep and corrosion are included as potential damage mechanisms under the repository conditions [2]. 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 tests (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 almost 10^4 also exceeds the usual range of extrapolation from laboratory experiments to real service conditions in most (or any) comparable engineering applications.

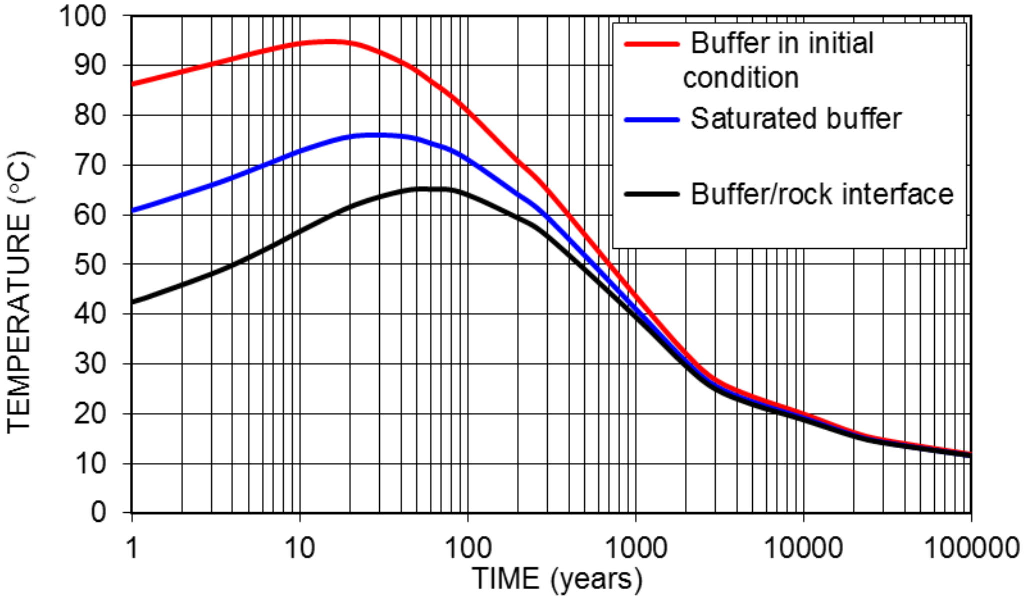

Figure 1. Predicted temperature evolution at the canister surface for EPR fuel [2]; the red curve assumes dry environment with a 10 mm gap around the canister.

2. Uniaxial creep behaviour

For uniaxial creep, notched bar and relaxation experiments, a 50 mm thick block of OFP copper plate with a reference code X579 was supplied by Posiva Oy. For testing of the strength of the oxide particle zone, Cu-OFP blanks from FSW-welded lid 108 were supplied by Posiva Oy for manufacturing of CT specimens from an updated type of FSW material. Metallography using light optical (LOM) and scanning electron microscopy (SEM) has been applied for the test specimens after testing.

For creep modelling, the combined Wilshire [3] and LCSP [4] models have been applied and further developed to support robust FE analyses under non-homogenous stress and strain fields.

The stress history dependence of Cu-OFP was studied by performing step-loading tests at 175 °C and 135 MPa in such way that a test was first loaded to 80%, then after a time period to 90% and finally after another time period to 100% load, as shown in Figure 2, where repeated primary creep stages are seen. The time step in test y568 was 3.5 days, one week in test y562 and two weeks in the test y565. It is seen that the one-week step loading resulted in a rupture time which is less than half of the rupture time of a test y553, which was loaded in a normal way to 100% at the start of the test. The rupture strain was not influenced by the step-loading. Another fully loaded test is running at 165 MPa as a reference test for a test series at 90 °C. This is the actual peak temperature, which the canister is going to experience during the first tens of years in the repository.

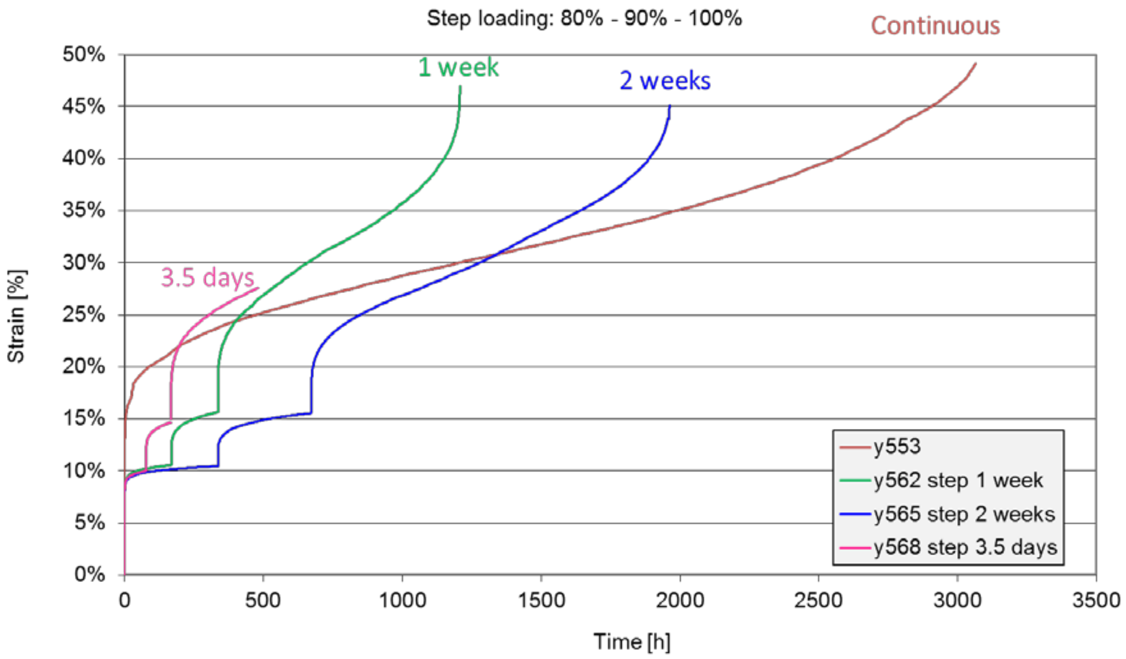

Figure 2. Strain vs. time curves of a fully loaded creep test (y553) at 175 °C and 135 MPa and of three tests which were loaded first to 80%, then to 90% and finally to 100% in 3.5 day steps (y568), in one-week steps (y562) and in two-week steps (y565)

This behaviour of repeated primary stages cannot be predicted by the current creep models and is most likely a result of stabilised dislocation structures collapsing and new dislocations being created when the stress is increased. In the repository the swelling pressure and consequently the mechanical stress which the canister experiences, will develop unevenly, at a different rate in individual positions and possibly in a step-wise manner. Therefore, at least some of the canisters will experience the external pressure in a step-wise manner. Rock shear would change the stress state very quickly.

3. Relaxation behaviour

Static and repeated relaxation testing for OFP copper was started at 80 °C and has been reported in [5]. Recently the testing has been extended to lower temperatures in order to be able to model the behaviour during the initial phase, when external pressure and the temperature of the canister are increasing. Stress relaxation periods ranging from 90 to 180 h in tensile stress were applied to test specimens in these tests. The strain was decreased to zero and increased back up to the peak strain between the relaxation periods. First, a test with five stress relaxation periods was performed at 60 °C. The peak strain was altered in this test from 0.32% to 0.64% to study the effect of peak strain and stress on the cyclic stress relaxation behaviour. Figure 3 shows the stress relaxation in the different cycles of the test at 60 °C.

The second test with five stress relaxation periods was performed at 40 °C with the strain ranging from 0.32% to 0.64% in tension in different stress relaxation periods, as shown in Figure 4. Again, the peak strain was altered in the different stress relaxation periods of this test from to study the effect of peak strain and stress on the cyclic stress relaxation behaviour at lower temperature.

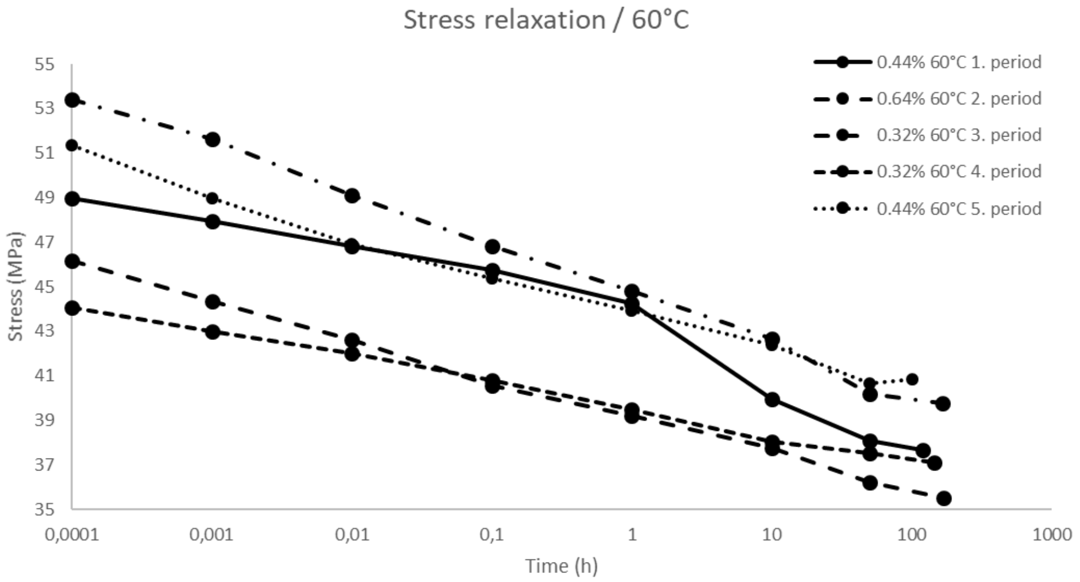

Figure 3. The stress relaxation in the different cycles of the test at 60 °C.

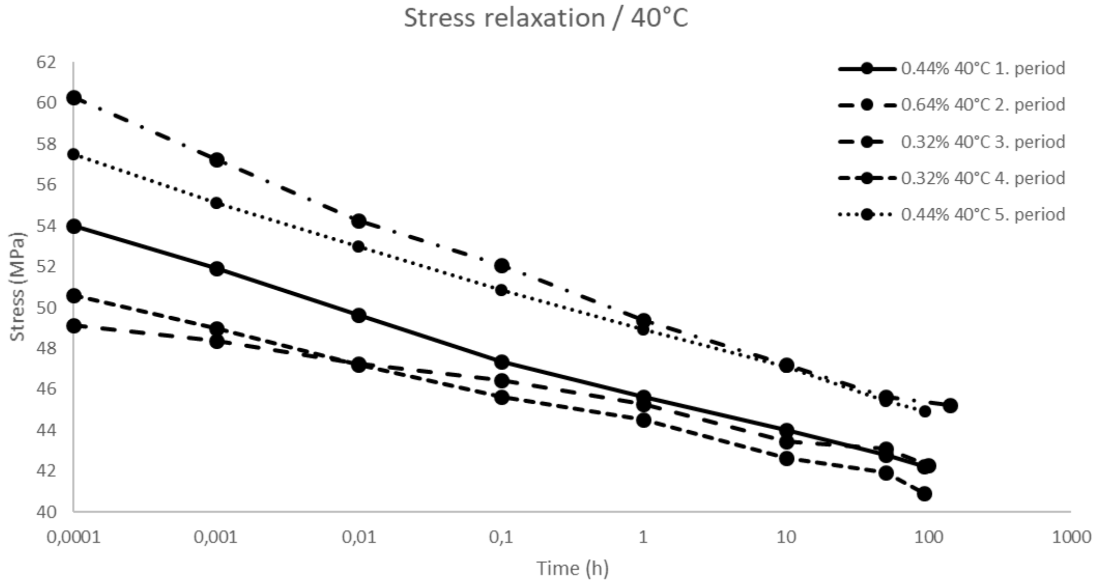

Figure 4. The stress relaxation in the different cycles of the test at 40 °C.

It was discovered in the earlier cyclic stress relaxation experiments at 80 °C (see Figure 5) that the amount of relaxed stress tended to decrease as the amount of reloads increased in the test. Discovering the same phenomenon in the tests with altered peak stress and strain in the different relaxation periods was not straightforward. Even though the stress and strain history affect the relaxation behaviour, also the peak stress and strain of the each cycle affect the relaxation behaviour. The proper interpretation of the conducted tests calls for deeper analysis and possibly some additional tests in the further studies.

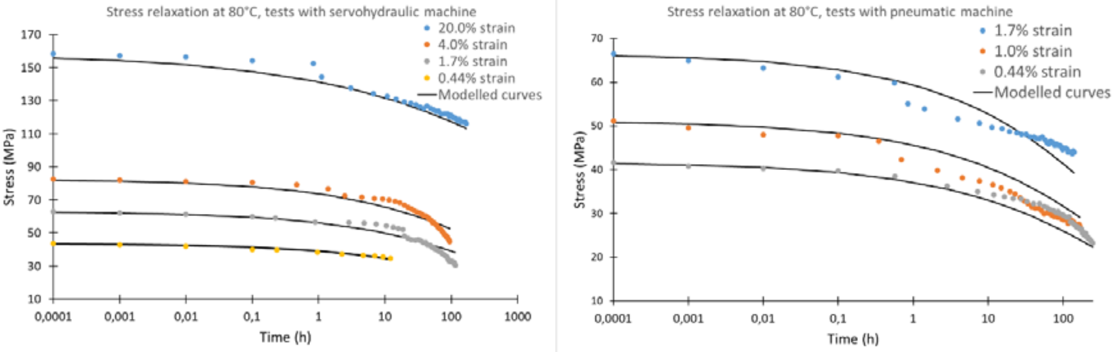

Figure 5. Single cycle stress relaxation tests (dots) and the model predictions (lines) at 80 °C.

An attempt has been made to describe stress relaxation based on the Kohlrausch relaxation model [6]:

$$\sigma = \frac{\sigma_0}{e^{\alpha \cdot \beta^t}} \tag{1}$$

$$\alpha = (\frac{\ln(T)}{a}) \cdot e^{\frac{-Q}{RT}} \tag{2}$$

$$\beta = (\frac{\log(\sigma_0)}{\sigma_{UTS}}) \cdot b \tag{3}$$

As can be seen from Equations (2) and (3), the α parameter carries an Arrhenius type temperature dependence and parameter β the stress evolution of the relaxation model. It can be concluded that the approach gives reasonably reliable predictions for single relaxation periods at least at 80 °C as can be seen in Figure 5, but it is under investigation whether the approach requires modification to properly take into account the effect of stress and strain history from previous cycles.

4. Behaviour of oxide particle layers

Posiva Oy provided canister lid material, friction stir welded in protective argon atmosphere, for testing of possible cracking in the oxide particle zone. CT-specimens from lid FSWL108 were machined such that the notch tip was located at or near the oxide particle zone, and creep tested at a reference stress of 60 MPa at 175 °C for targeted testing times of 1.000 and 10.000 hours. After testing, the specimens were sectioned and hydrogen annealed in order to reveal the oxide particle zone that was then subjected to metallographic inspection by optical and scanning electron microscopy, see Figures 6 - 8. A more detailed report of this work has been published in [7].

The results showed considerably reduced amount of oxide particles in comparison to the old welds welded in air (Figure 7). In an old weld tested at a reference stress of 35 MPa at 175 °C for 50.000 hours, the oxide particle zone had cracked (see Figure 8), although the loading level was much lower than for the new welds that showed no similar cracking.

The specimen 108-2, which was tested for 10.000 hours, was subjected to EBSD inspection. An image quality map with grain boundaries is shown in Figure 9. Local average misorientation image is shown in Figure 10, which indicates that the oxide particles have not caused additional deformation around them. Also, there is no indication of cracking.

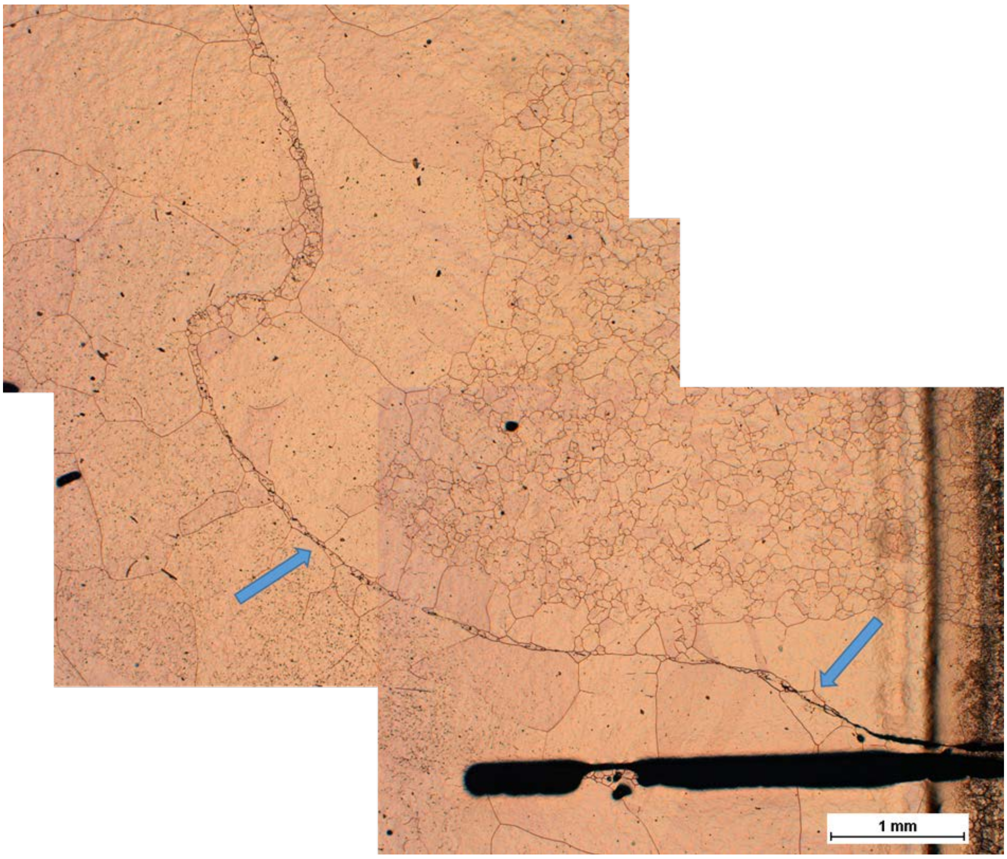

Figure 6. Tip of the wire eroded notch, the joint line hooking (right arrow) and the oxide particle zone (left arrow) in CT-specimen 108-1 after testing and hydrogen annealing

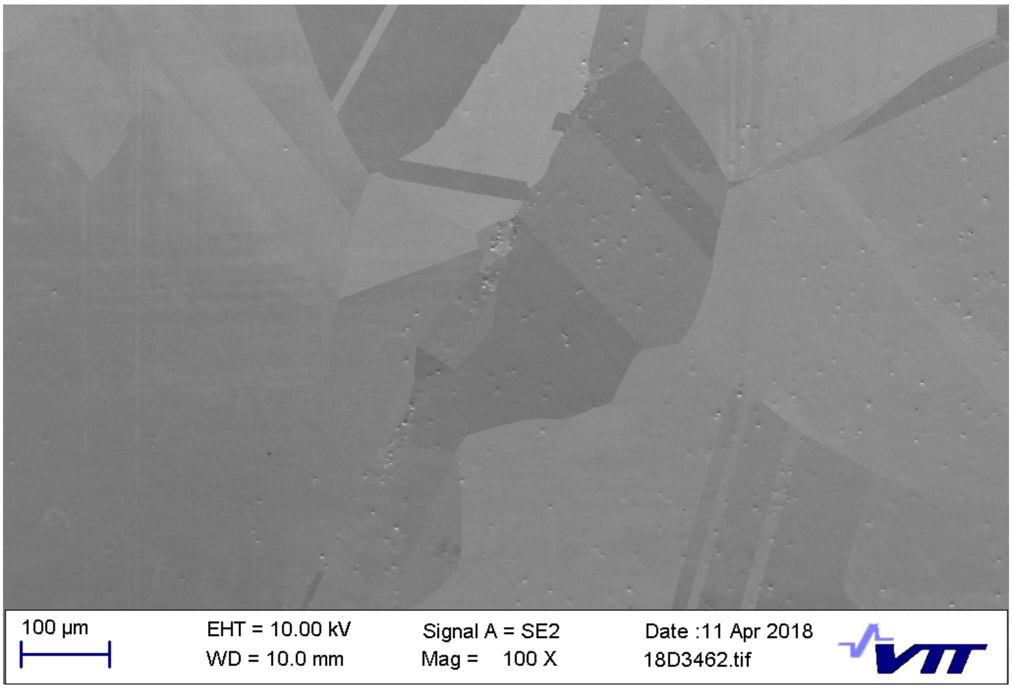

Figure 7. Details of oxide particle zone.

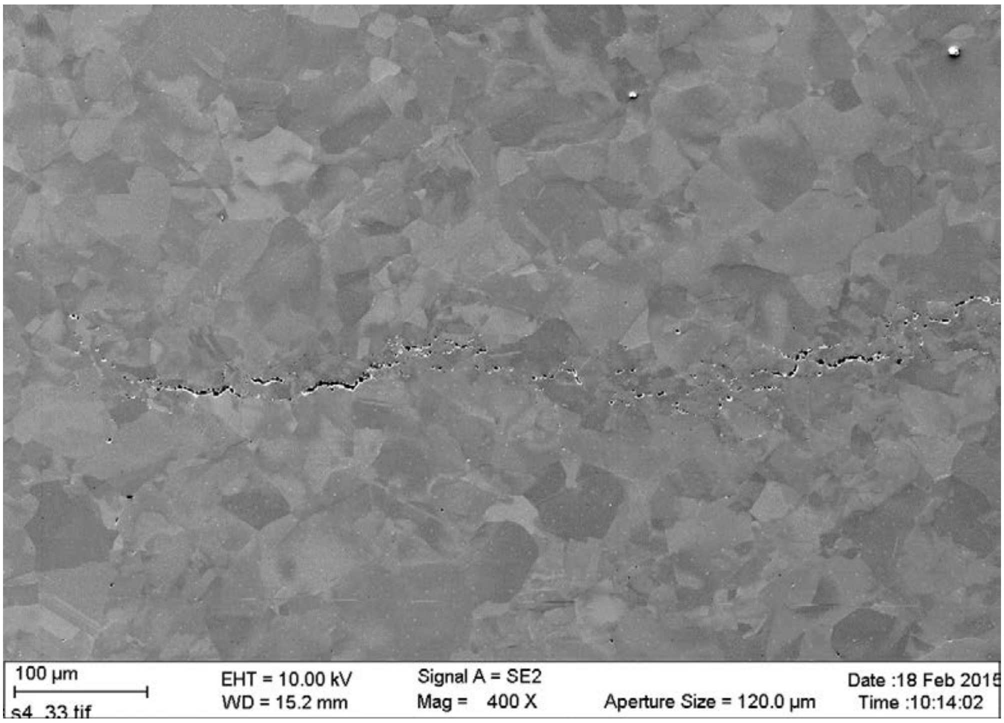

Figure 8. Cracking in the oxide particle zone in the KYT CT-specimen after 50.000 hours of testing at 35 MPa / 175 °C

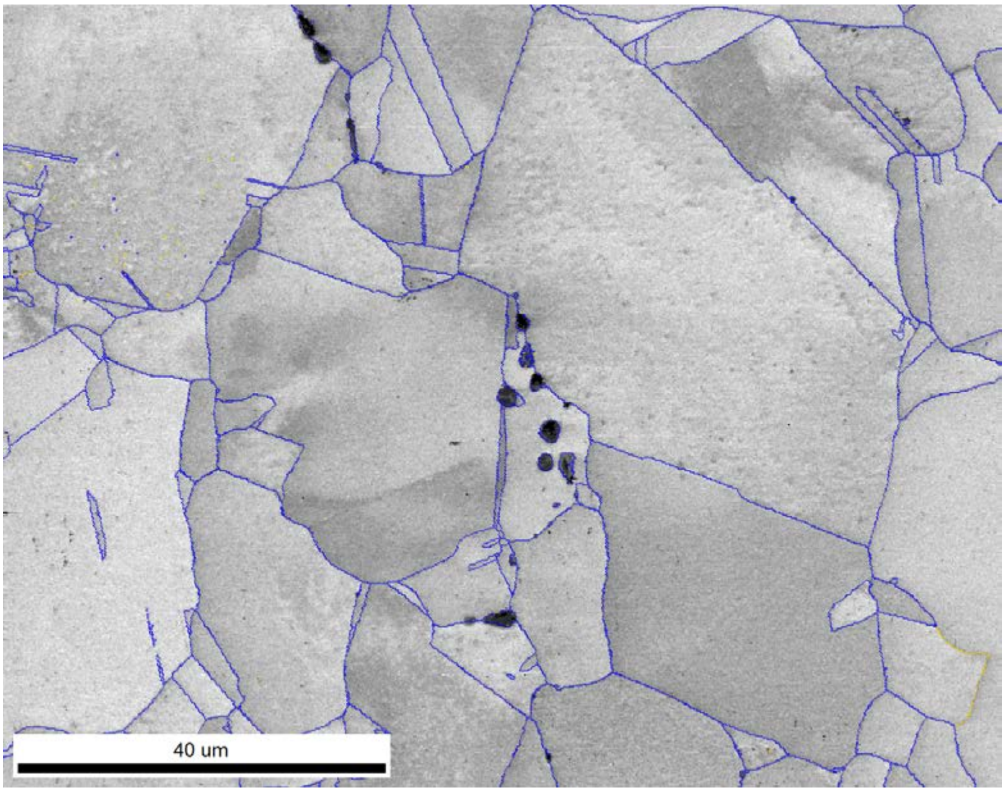

Figure 9. EBSD image quality map of grain boundaries in the oxide particle zone of specimen 108-2.

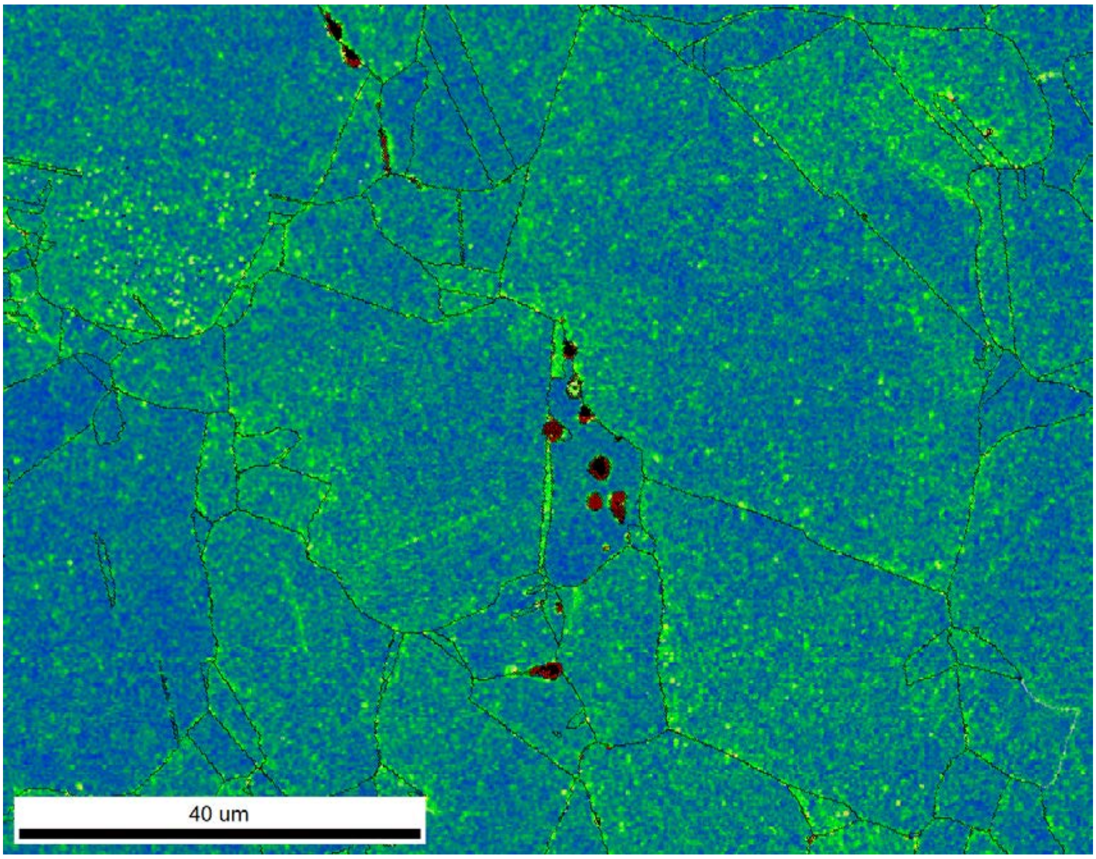

Figure 10. Local average misorientation in the oxide particle zone of specimen 108-2.

5. Conclusions

Behaviour of Cu-OFP has been modelled based on creep and relaxation test results in order to facilitate a full 3D creep FE analysis for the nuclear waste disposal canister with a cast iron insert and a copper overpack under external pressure. Stress history dependence of copper has been tested. The friction stir welding (FSW) process has been modified by changing the direction of rotation of the welding tool, which has eliminated the turn-back of joint line hooking. In order to reduce the amount of oxide particles, the FSW process is now conducted in protective atmosphere. The behaviour of oxide particle layers in the old and new welds has been tested.

The 3D FE analysis has to be repeated after the direction of rotation of the welding tool has been reversed and the welding conducted in protective atmosphere. Also the relaxation behaviour has now been tested in lower temperatures to represent the initial phase when the canister temperature is increasing. Modelling the behaviour of Cu-OFP during the slow increase of temperature and external pressure remains a challenge as creep and relaxation processes will act simultaneously.

References

1. Finnish Research Programme on Nuclear Waste Management (KYT) 2015-2018.

2. Raiko, H. Canister Design 2012. Report POSIVA 2012-13, Posiva Oy.

3. 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.

4. Holmström, S. Engineering tools for robust creep modeling. Dissertation. Espoo, VTT, 2010. VTT Publications 728. 94 p. + app. 53 p.

5. Juhani Rantala, Rami Pohja, Pertti Auerkari, Experimentally verified model based predictions for integrity of copper overpack – Annual report 2017. Espoo, VTT, 2018. VTT Research Report VTT-R-01499-18.

6. Auerkari, P., Pohja, R. & Nurmela, A., Relaxation of OFP copper. Espoo, VTT, 2014. Research Report VTT-R-00366-14.

7. J. Rantala, CT-specimen testing of oxide particle layers in a FSW lid joint after welding in argon, VTT, 2018. Research Report VTT-R-06729-18.