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Deformation Mechanisms of Nuclear Waste Canister

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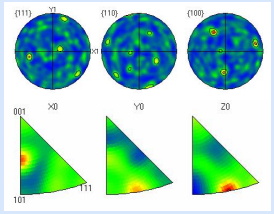
Introduction

In Finland, spent nuclear fuel will be stored deep in the bedrock. One of the barrier layers protecting the environment from the spent nuclear fuel is a 50 mm thick copper corrosion canister. Different parts of the copper canister have inhomogeneous grain structures and the canister itself contains discontinuities and welds as well as possible minor defects, which cause stress concentrations. These regions have a significant influence on the deformation of the canister during its life, and their impact on the life expectancy of the copper canister must be known. The effects of deformation, residual stresses, variation in the grain size, and localization of deformation caused by local variations in the degree of deformation are the most important factors in the life expectancy of a spent nuclear fuel canister, as they affect the creep, stress corrosion cracking and localization of deformation on certain critical points of the canister. During the recent years the possibility of copper corrosion in oxygen-free pure water as a result of hydrogen forming has been highlighted. Corrosion is assumed to increase the amount of hydrogen in copper and making the copper brittle. Only a few studies exist of hydrogen embrittlement of copper.

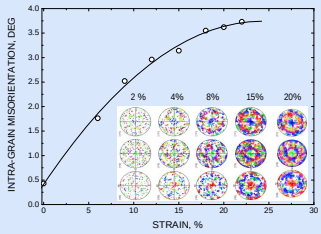
The aim of this project was to determine a calibration curve based on the degree of deformation in the copper material as well as to study the localization of plastic deformation in different parts of the copper canister. Also hydrogen absorption and its effect on the mechanical properties of copper were studied. The microstructures of the welds were characterized using modern orientation microscopy methods (FEG-SEM/EBSD) and nanoindentation was used to locate the local elastic and plastic discontinuities of the microstructure. The results of this research project are very important in understanding the deformation mechanisms and reliably modeling and estimating the expected lifetime of the copper spent nuclear fuel canister.

Calibration curve

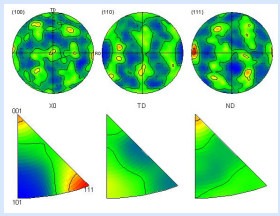
The calibration curve can be used for quantitative strain measurement, but the method is sensitive to different EBSD parameters (step size, accuracy of pattern recognition, etc.) as well as the grain size and the stacking fault energy of the material. Further research in this field is highly important.



Pole figures and inverse pole figures of the samples strained to 2 %.

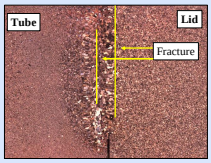


Calibration curve for determining the degree of local deformation in Cu-OFP.

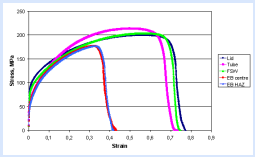


Pole figures and inverse pole figures of the samples strained to 15 %.

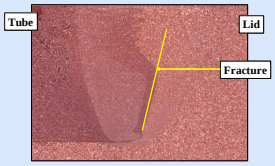
Localization of plastic deformation in different parts of the nuclear waste canister



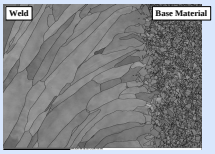
Macrograph of the transverse section of the EB weld. Fracture occurred either at the centre of the weld or at the interface between the weld and the lid material.



Stress-strain curves of the different parts of the spent nuclear fuel canister.



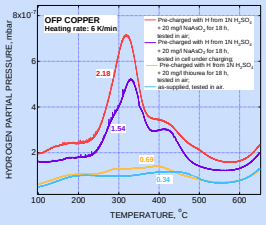
Macrograph of the transverse section of the FSW weld. Fracture occurred at the line of entrapped oxide particles (marked by a yellow line).



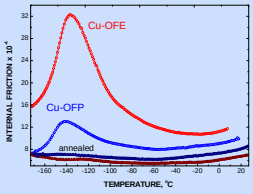
Top view of the EB weld. The large grain size gradient between the EB weld (left) and the base material (right) is clearly seen.

Localization of plastic deformation in the different parts of the copper nuclear waste canister (forged lid material, extruded tube material, electron beam weld EB, and friction stir weld FSW) has been studied using large samples which contain the entire weld joint and optical strain measurement system. It was noticed that the strength and elongation to fracture of the FSW welds were similar to those of the base materials, while they were considerably lower in the EB weld. The EB weld samples fracture either at the centre of the weld due to the large grain size or at the HAZ between the weld and the lid due to the large grain size gradient. The FSW weld samples fractured at the line of entrapped oxide particles.

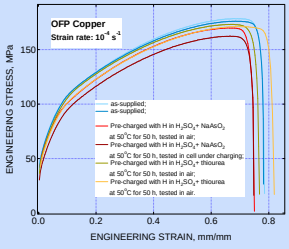
Hydrogen effect



Hydrogen TDS spectra of the OFP copper after testing under different conditions. Total amounts of hydrogen in wt. ppm obtained with thermal extraction method (LECO) are shown by number of corresponding color.



Temperature dependencies of internal friction for Cu-OFE (oxygen content less than 5 wt. ppm,) and Cu-OFP (oxygen content less than 5 wt. ppm, phosphorous less than 70 wt. ppm,) in high vacuum annealed and in high vacuum annealed and hydrogen charged states.



SSRT of as-supplied and H-pre-charged OFP copper.

Hydrogen uptake in the electrochemical charging procedures was monitored with hydrogen thermal desorption spectroscopy (TDS) method.

Testing in air of the hydrogen-charged copper results in a minor effect, while testing under applied electrochemical cathodic potential leads to about 15 % reduction of the plastic flow in the whole range of the plastic elongation of the specimen.

Electrochemical hydrogen charging of copper induces in it distinct internal friction peak in vicinity of –140 °C, which also confirms presence of hydrogen in solid solution of copper after the charging.

Summary

Calibration curve for determining the degree of local deformation using FEG-SEM/EBSD equipment has been completed for Cu-OFP base material.

Based on the results obtained in this study it can be concluded that deformation occurred quite uniformly in all the samples except for the EB weld. In EB welds the deformation localizes mainly to the large grains in the middle of the weld or at the fusion line between the lid and the EB weld due to the very steep grain size gradient. It was also noticed that in EB welds the extruded tube material is elongated more than the forged lid material. The tensile strength for EB weld was lower than that for the other materials, 175 MPa and 200 MPa or higher, respectively. Elongation to fracture was similar in the base in the base materials and the FSW welds, but considerably lower in the EB welds.

The minor hydrogen effect in the testing in air is probably caused by relatively high hydrogen diffusion and dislocation transport of hydrogen to the specimen surface in the course of plastic straining. Testing in the cell with applied potential, however, follows with a permanent ingress of hydrogen of high fugacity into the specimen. It is assumed that hydrogen of high fugacity in copper may induce the gas-filled porosity [Wampler, W. R. , Schober, T. and Lengeler, B.(1976). Phil. Mag., 34: 1, 129 — 141] which result in the reduction of the plastic flow stress.

Observed internal friction peak is due to interaction of introduced hydrogen with dislocations. An amplitude of the internal friction peak in P-doped Cu (OFP) is smaller, while parameters of the hydrogen charging were the same for the both copper grades. The effect of phosphorous is under study.

Acknowledgements

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List of publications

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2. Savolainen, K., Saukkonen, T., Mononen, J., and Hänninen, H. (2008) Entrapped Oxide Particles in Friction Stir Welds of Copper. 7th Intenational Symposium on Friction Stir Welding. Awaji Island, Japan, 20-22 May. 20 p.
3. Savolainen, K. (2008) Friction Stir Welding and Processing of Copper. TKK Reports MTR-1/2008. 83 p.
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5. Savolainen, K., Saukkonen, T., and Hänninen, H. (2009) Optical Strain Measurement of Plastic Strain Localization in Nuclear Waste Copper Canisters. 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20). Espoo, Finland, 9-14 August. 9 p.
6. Savolainen, K. Saukkonen, T., and Hänninen, H. (2010) Localization of Plastic Deformation in Copper Canisters for Spent Nuclear Fuel. In: Auerkari, P. and Veivo, J. (eds.) Proceedings of Baltica VIII – International Conference on Life Management and Maintenance for Nuclear Power Plants. Espoo, Finland: VTT. Pp. 163-177.
7. Ivanchenko, M., Yagodzinskyy, Y., and Hänninen, H. (2011) Hydrogen-induced Mechanical Losses in Oxygen-Free Copper. 16th International Conference on Internal Friction and Mechanical Spectroscopy. Lausanne, Switzerland, 3-8 July. To be published.
8. Yagodzinskyy, Y., Todoshchenko, O., Saukkonen, T., Savolainen, K., and Hänninen, H. (2011) Effect of Hydrogen Absorption on Mechanical Properties of Pure Copper. Eurocorr 2011 – The European Corrosion Congress. Stockholm, Sweden, 4-8 September. To be published.
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10. Hänninen, H, Yagodzinkyy, Y., Saukkonen, T., and Savolainen, K. (2011) Hydrogen Embrittlement of Pure Copper. Scripta Materialia. To be published.
11. Saukkonen, T., Savolainen, K., and Hänninen, H. (2011) Nanoindentation Study of Elastic Anisotropy in Electron Beam Welds of OFP Copper. Journal of Nuclear Materials. To be published.
12. Saukkonen, T., Savolainen, K., and Hänninen, H. (2011) Determination of Calibration Curve for Measuring Plastic Strain by EBSD in Oxygen-Free Copper. Scripta Materialia. To be published.