The Eddy Current Inspection for Detection of Surface and Near Surface Defects in Copper Components and an Electron Beam Weld

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ABSTRACT

The surface inspection of copper components and even EB-weld plays important role in acceptance of nuclear fuel disposal. To inspect these components there are two main reasons: Manufacturing and handling defects of components.

In following study there were developed the software, visualising tools for eddy current measurements and eddy current sensors for detection of unwanted defects. The eddy current equipment was manufactured by the IZFP and the visualizing software in active co-operation with Posiva and IZFP during the inspections. The inspection procedure was produced for during the development of the inspection techniques. The aim of the inspection method development is to qualify the method for surface and near surface defect detection and sizing according to ENIQ. The study of technical justification will be carried out in 2009. At the same time the defect catalogue will also gathered and gaining experience from measurements of Posiva's research manufacturing will be continued.

The depth of penetration in copper components in eddy current testing is rather small. To detect surface breaking defects eddy current inspection is a good solution. To develop a simple approach two ways technique was used:

- higher frequencies to detect surface defects and determine the dimension of the defects except of depth, for small depths higher frequencies was applicable
- lower frequencies were used to detect defects having a ligament and for sizing of deeper surface breaking defects

The higher frequencies were 30 kHz and correspondingly the lower frequencies were 200 Hz. The higher frequency probes were absolute bobbing coils and lower frequency probes combined transmitter-several receiver coils. To evaluate the both methods calibration blocks were manufactured by the FNS for copper tube, copper lid and copper weld inspections. These calibration specimen consisted of mainly electron discharge machined notches and holes of varying shapes, lengths and diameters in the range of 1 mm to 20 mm of depth. One copper tube specimen of 61 defects and one copper lid specimen having 152 defects were manufactured. For weld inspection 2 weld blocks was cut off and 29 reference defects for UT and ET were manufactured in those 2 specimen.

Several copper tubes, lids and welds were measured in order to obtain performance of the eddy current inspection for detection of surface defects. There will be some metallographic studies to identify indications origin and the results of these studies will be reported later in conjunction of these eddy current measurements. The preliminary measurements show the capability of developed eddy current measurements to detect and size surface defects and show capability to see indications having ligament up to 5mm.

INTRODUCTION

The canister should hold its tightness for at least 100 000 years. The following requirements have been given for the tightness of the canister:/1/

- A good original tightness (with high quality requirements and extensive inspections)
- A good corrosion resistance (use oxygen-free copper as a copper material)
- Sufficient mechanical strength (ensure with tensile tests or similar).

The canister must limit the radiation exposure on its outer surface, in order not to limit the handling or transport. There should not be considerable radiolysis in the ground water and the construction of
inner part of the canister should keep the fuel element in sub critical state even when the empty space of the inner part of the canister is filled with water.

The methods available for the inspection of copper tubes are ultrasonic and eddy current testing. Ultrasonic inspection will be carried out with linear phased array probes. In ultrasonic phased array inspection the surface area is not covered properly due the ringing of received A-scan signals, which is similar to the problem of inspecting near field area using conventional single crystal ultrasonic probes. Grain size variation poses additional challenges to ultrasonic testing /2/. The used eddy current inspection covers surface area and at the same time completes the ultrasonic inspection. The inspection requirement concerning the defects and geometry of components will be discussed as well as the basics of eddy current inspection of those components. Parametric studies give support for inspection.

**COPPER COMPONENTS TO BE INSPECTED**

The designed spent nuclear fuel canister consists of a copper tube and lid, a nodular cast iron insert and steel lid. Figure 1 shows the copper components as well as the closure weld between them. All copper components and the closure weld will be inspected with eddy current technique (ET). These components may contain different types of manufacturing and handling defects.

Figure 1 - Copper tube is seen on the left and the EB-weld joining the tube and the lid on the right.
Table 1- Possible defect types in copper components, FS- and EB-welds and defect detectability with ET.

Table 1 shows the possible defect types of different copper components and which of them can be inspected with eddy current inspection. Defect types are handled in the literature. /3,4,5,6/

EDDY CURRENT INSPECTION SYSTEM AND ET-COILS

The 32 channel eddy current device is based on two inspECT® eddy current boards. Each board can multiplex up to 16 frequency channels. With the external multiplexer box one board can drive 16 probes. Frequency and probe multiplexing can be mixed to get multi frequency data of a sensor array with just one scan. The device has a two axis coordinate interface for scanning with manipulators. Data connection to the PC over Ethernet has no need of a real-time operating system as the data is buffered in the device and synchronized with the coordinates.

![Figure 2 - Block diagram of the 32 channel ET-device.](image-url)
Technical data of the inspECT® board are following:

**Digital**
- DUAL DSP Core (SHARC for real-time data processing, BLACKFIN for communication)
- Firmware, flashing (updating) via Ethernet
- 8 Opto-decoupled real-time outputs / 8 Opto-decoupled real-time inputs
- 8 Multiplexer-trigger outputs to control the sensor multiplexer

**Analogue**
- Dual-NCO for test frequencies ranging from 100 Hz to 10 MHz
- Sensor driver ($R_i = 50 \, \Omega$ and $2.2 \, V_{ss} at 50 \, \Omega$)
- Sensor input $50 \, \Omega$, alternative differential input at $1 \, k\Omega$
- 10-50 dB HF gain with overload control
- Demodulation and anti-aliasing filter
- 2 x 16-Bit analogue to digital converters, 200 kHz sampling rate

The software package inspECT® is a combination of a multi channel data acquisition system and powerful C-Scan analysing software which makes it easy to analyse the recorded data and produce indication reports. The equipment is shown in Figure 3. The inspection is monitored by the laptop shown in Figure 4 and measurement will be carried out by 2 different probe types - high frequency probe using frequency of 30 kHz and low frequency probe using frequency of 200 Hz. Both probes are shown in Figure 4. For copper inspection low frequency probe was suggested by the Uchanin et al., 2003/7/. This eddy current coil was using four receivers and the transmitter was in the middle of that coil system and the frequency used in the measurements was 2 kHz.
Table 2 - The evaluated depth of penetrations of used frequencies in the eddy current inspections. HF is eddy current using high frequency technique and LF is using low frequency technique.

<table>
<thead>
<tr>
<th>EC-TECHNIQUE</th>
<th>$\delta$ [mm]</th>
<th>$\rho$ [m(\Omega)cm]</th>
<th>$f$ [Hz]</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.38</td>
<td>1.72</td>
<td>30000</td>
<td>1</td>
</tr>
<tr>
<td>LF</td>
<td>4.64</td>
<td>1.72</td>
<td>200</td>
<td>1</td>
</tr>
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</table>

The depth of penetration can be estimated simply with Equation 1. The calculated depths of penetration for the inspection frequencies are shown in Table 2. The visualization of the depth of penetration is shown in Figure 5, which shows the computed eddy current density in depth direction using modeling software Civa version 9.2. All dimensions are similar to the real probe shown in Figure 4.

$$\delta = 50 \frac{\rho}{\sqrt{f \mu}}$$

where $\delta$ is the standard depth of penetration, $\rho$ the conductivity of copper, $f$ the used frequency of the coils and $\mu$ the relative permeability.

PARAMETRIC STUDY WITH COPPER PLATE

Five copper plates with about 100 reference defects were designed and manufactured for the parametric study /8/. Figure 6 shows the results of the measured data from the high frequency coils (in the top) and low frequency coils (in the bottom). It is clearly seen that the diameter of the defect can be estimated by the high frequency coils and that the low frequency probe can be used for estimating the depth of the reference defect. The surface sizes of the indications are still overestimated. Surface size evaluation must be developed to be more accurate.

Figure 5 - Visualization of eddy current density for low frequency probe using the frequency of 200 Hz using Civa 9.2 is on the left and construction of the modeled eddy current probe on the right.
Indications of several defects in polar coordinates show how the angle of indications reveals the depth of the defects. The inaccuracy of depth sizing will be studied. As seen in Figures 7 and 8, the indications will saturate at the depth of approximately 10 mm for surface breaking defects. This means that it is possible to estimate the depths of the indications up to 10 mm, after that the reliability decreases clearly. It is possible to distinguish between volumetric and planar types of defects. These two type of defects have their own defect depth sizing curves. It is important first to evaluate the type of indication and surface area to improve the accuracy in sizing.

Figure 6 - Comparison of C-scans between low frequency (upper) and high frequency (lower) measurements.

Figure 7 - Reference defect depth variations from a U-type of defect presented in Figure 8 shows variation in amplitude and angle in polar coordinate presentation for low frequency coils.
Figure 8 - Principles of defect sizing: change of the indication angle depends on the depth of the defect (left) and evaluation is based also on the amplitude of detected indications (in the middle) and U-type of indication (right).

The evaluation can be based either on the measured amplitude or on the angle of indication as shown in Figure 7. Figure 8 shows the preliminary results of sizing U-type defects. This type of reference defect was chosen because such defects were detected during inspection of welds. The welding process and machining after welding can also produce defects which do not open to the surface, meaning that there is a so-called ligament between the defect and the surface. If this ligament is not too thick the defects can be detected in the eddy current testing. As shown in Figure 9, the defect having ligament up to 5 mm was still detectable. The ligament thickness can be evaluated from the angle of the indications.

INSPECTION OF COPPER TUBE

Diameter of the copper tube is about 1050 mm and the wall thickness about 50 mm. Eddy current inspection is used to inspect the outer surface of the tube. A reference specimen with about 60 reference defects was designed and manufactured for calibration. Surface breaking reference defects are shown in the C-scan of the calibration tube (Figure 10, on the left). Colors differing from grey show the positions of the reference defects in the specimen. The results of inspecting a 2 m long tube are shown in Figure 10 on the right. Some of these indications (notches) are shown in Figure 11 using low frequency coils. The amplitude and angle of indications increase clearly until the depth of 20 mm. The length of the reference defects was 40 mm.

Figure 9 - Effect of ligament on the angle of indications. C-scan and amplitude scans are shown on the left and the dependency of the angle of indications on the ligament is shown on the right.
Figure 10 - C-scans from the tube reference specimen and the tube measured with high frequency coils.

Figure 11 - X-Y-presentation (upper), polar coordinate presentation (lower-left) and C-scan from a reference specimen in the notch series, with notch depths varying from 1 mm to 20 mm (lower right).

Figure 12 - Coil setup for lid inspection.
INSPECTION OF COPPER LID

The copper lid is joined to the copper tube by EBW. The outer surface of the lid is inspected with ET prior to welding. The coil set-up for the inner and upper parts of the lid are shown in Figure 12. A reference specimen with about 150 reference defects was designed and manufactured for eddy current and ultrasonic testing, Figure 14. Eddy current measurements were carried out using both high and low frequency coils. Results with high and low frequency coils are shown in Figures 13 and 14, respectively.

INSPECTION OF COPPER WELD

The sealing weld is made by electron beam welding. The method is described briefly in /3/. The grain size varies from 60 µm to several millimeters. The grain size variation has a strong effect in ultrasonic testing /2/, but in eddy current testing the effect is not so large. The regular inspection area for a weld is the weld width +10 mm base material on both sides. In this case the whole weld surface was measured with both techniques. The inspection volume reaches to 5-10 mm from the weld surface.

Figure 13 - C-scans from lid inspection with high frequency coils - upper (left) and inner (right) area of the lid.

Figure 14 - C-scan from the inner part of the lid with low frequency measurements (left) and the lid reference specimen (right)
The correctness of the welding parameters is verified using test plates before making the real size welds. Figure 16 shows indications obtained by both low and high frequency methods as well as a photo of the surface of the welded test plate. It can be seen that the high frequency method gives a good visualization of the surface size of the defect. The depths of those indications will be studied more carefully and reported later on. Higher angle and amplitude level indicate higher depth of defect.
in low frequency measurements. These indications are shown in Figure 17 and the estimated angles of 2 largest defects are 49.8° and 43°.

Some of these ET indications will be verified with metallographic studies. About 50 NDT indications will be studied and at least 10-15 of them are detected in the eddy current testing. Figure 18 shows a part of machined EB-weld and indication volumes which have been cut off for a more accurate metallographic evaluation.

Figure 16 - C-scans using low frequency (upper) and high frequency (middle) and photo from the surface of EB-weld in the plate specimen (lower).

Figure 17 - Eddy current indications in polar presentation from plate EB-weld specimen. Large indication is defect 2 and smaller indication is defect 1 in Figure 16.
The detectability of defects in copper component and cast iron inserts have been reported in different studies /9, 10/. POD studies for copper components and EB-welds will be carried out and reported 2010. The POD for weld will be carried out according to plan presented in /11/.

SUMMARY AND CONCLUSIONS

In this study the eddy current inspection method has been developed to be applicable for the inspection of copper components and EB-welds. The inspection of copper component is based on using both low and high frequency eddy current testing. In this case high frequency refers to 30 kHz low frequency to 200Hz. The sizing capability was greatly increased with the use of low frequency probe. The sizing is reliable up to 10 mm to surface breaking defects. The defects with ligament of 7 mm can be detected, but the limit for a reliable detection is at the moment 5 mm. The sizing capability of the eddy current method will be verified with metallography.

The results are based on a large scale study of real size reference specimens and defects as well as real defects. The real size components are similar to those in production and in encapsulation plant. The developed low frequency probes will be optimised in the future for higher depths. The metallographic verification of detected indications is continuing.

Preliminary inspection procedures were developed for all copper components in this study. The aim of this work is to qualify the eddy current inspection according to ENIQ and the Finnish practice in qualification. Technical justifications for this type of measurements will be developed in 2010.

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