Flux Gate Magnetometry Applied to RF Cavities

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Outline:

Magnetometry applied to

- Buffered Chemical Polishing (BCP)
- Electropolishing

Eddy Current NDT applied to

- Evaluate of Nb Resistivity
- Detect of defects on Niobium surface
Typical surface treatment for the RF cavity

In both case of

- bulk Niobium Cavities
- Nb Sputter coated Cu cavities

The surface must be treated to remove sources of rf losses

Mainly two treatments are used to reach a smooth surface:

- chemical polishing
- electropolishing

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The best surface integrity ➞ Quality control

Non invasive contact-less Magnetic sensors

Monitoring the chemical/electrochemical etching
### Typical Magnetic sensors characteristics in unshielded environment

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hall probe</strong></td>
<td>± 10 mT</td>
<td>0.8 μT /√Hz @ 1Hz</td>
</tr>
<tr>
<td><strong>Flux Gate</strong></td>
<td>± 70μT</td>
<td>10 pT/√Hz @ 1Hz</td>
</tr>
<tr>
<td><strong>GMR</strong></td>
<td>± 50 μT</td>
<td>0.1 μT /√Hz @ 1Hz</td>
</tr>
<tr>
<td><strong>SQUID</strong></td>
<td>± 1μT</td>
<td>0.3 pT/√Hz @ 1Hz</td>
</tr>
</tbody>
</table>

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Basic Considerations

In the BCP process there is not metal dissolution … …

The Nb is oxidized by HNO₃ → The oxide is reduced by HF in a soluble salt → The H₃PO₄ works as a reaction moderator

All these processes are based on a charge transfer

If there is a charge transfer a magnetic field is detectable

The detected magnetic field is proportional to the dissolution rate

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Passing from Nb BCP 1:1:1 to BCP 1:1:2 (increasing the $\text{H}_3\text{PO}_4$ percentage) the magnetic signal detected becomes monotonically stronger.

- BCP 1:1:1
- BCP 1:1:1.1
- BCP 1:1:1.2
- BCP 1:1:1.3
- ...
- BCP 1:1:1.9
- BCP 1:1:2
Rectangular electrolytic cells of different dimensions with copper electrodes.

The solution used:
- 55% Phosphoric acid
- 45% n-buthanol

Flux Gate 1st order electronic gradiometer
It detects the “in plane magnetic field” component and is less sensitive to the environmental noise than a magnetometer.
Static measurements

Fixing the probe on the electrode and driving in voltage it is possible to measure:

The H-V Characteristics of Elecropolishing just replies the I-V polarization curve

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Corrosion Rate

Considering the motion of particles, the numbers of carriers is:

\[ n = \frac{\mu_0}{4\pi} \frac{jSl}{Br^2} \]

Number of carriers

Faraday law

\[ w = \frac{jStM}{nF} \]

Corrosion rate

\[ \frac{w}{t} = \frac{4\pi BMr^2}{\mu_0 lF} \]

In the case of cells 50 mm long and different width:

<table>
<thead>
<tr>
<th>Cell width (mm)</th>
<th>(w[g]) at 4V by balance</th>
<th>(w[g]) at 4V by H</th>
<th>(w[g]) at 7V by balance</th>
<th>(w[g]) at 7V by H</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.012</td>
<td>0.011</td>
<td>0.025</td>
<td>0.048</td>
</tr>
<tr>
<td>16</td>
<td>0.023</td>
<td>0.020</td>
<td>0.035</td>
<td>0.020</td>
</tr>
<tr>
<td>24</td>
<td>0.05</td>
<td>0.032</td>
<td>0.13</td>
<td>0.035</td>
</tr>
</tbody>
</table>

\(\mu_0 = 4\pi \times 10^{-7} \text{ Vs/Am}\)

\(M_{\text{Cu}} = 63.456 \text{ g/mole}\)

\(F = 96500 \text{ As/mole}\)

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Dynamic measurements

Starting from the magnetic field distribution the current density across the electrodes can be obtained

Moving the Flux Gate (FG) probe over electrodes it is possible to monitor the electropolishing activity

Magnetic field distribution over the anode

Magnetic field distribution over the cathode

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Electromagnetic Inversion

The rectangular cell has been approximated to a finite short wire which generates a magnetic field expressed by Biot-Savart law:

\[
B(r) = \frac{\mu_0}{4\pi} \int \frac{J(r') \times (r - r')}{|r - r'|^3} d^3 r'
\]

With \( J \) current density and \( r \) the distance where the magnetic field is measured.

Considering the in plane component of the field

\[
B_y(x, y) = \frac{\mu_0}{4\pi} l \cdot z \cdot \int \int \frac{J_x(x, y)}{\left(x^2 + z^2\right)^{3/2}} dx dy
\]

This formula represents the convolution between the current density \( J \) and Green function \( G \)

\[
G(x, y) = \frac{\mu_0}{4\pi} l \cdot z \cdot \frac{1}{\left(x^2 + z^2\right)^{3/2}}
\]

By using the convolution theorem it is possible to rewrite the (1) in the Fourier space as:

\[
b_y = g \cdot j_x
\]

\[
j_x = \frac{b_y}{g}
\]

Current density in the Fourier space

The inverse Fourier trasformation of \( j_x \) gives the current density \( J \).
Below the I-V plateau

Magnetic field distribution

anode

cathode

Current distribution

anode

cathode

In the I-V plateau

Magnetic field distribution

anode

cathode

Current distribution

anode

cathode

Above the I-V plateau

Magnetic field distribution

anode

cathode

Current distribution

anode

cathode

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Real time Magnetic Field imaging

Magnetic field distribution

Current density distribution

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Cells with different cathode geometries

![Graph showing current density (A/mm²) vs. distance (mm)](image)

- Flat cathode
- Curve cathode

$$w = \frac{jStM}{nF}$$
Evaluation of Niobium Resistivity
By Pulsed Eddy Current technique

Niobium sample | RRR | $\Delta t$ (µs) | Conductivity ($\Omega \cdot m$)$^{-1}$ | Resistivity ($\Omega \cdot m$)
--- | --- | --- | --- | ---
Reactor Grade | 50 | 251 | $0.125 \cdot 10^8$ | $8 \cdot 10^{-8}$
Wa Chang | 230 | 267 | $0.133 \cdot 10^8$ | $7.5 \cdot 10^{-8}$
Tokio Denkai | 250 | 271 | $0.135 \cdot 10^8$ | $7.4 \cdot 10^{-8}$

Eigenvalue of D’alambert equation

$z^2 = \frac{\Delta t}{\mu \sigma}$
Detection of defects on Niobium surface

Eddy current technique using ELOTEST B300
Working frequency = 1.4MHz

Depth < 0.1mm
Conclusions

Electromagnetic technique using magnetic sensors as magnetometers or gradiometers allows:

- monitoring the ongoing corrosion during the electropolishing of metals surface
- evaluation of Nb room temperature resistivity with a sensitivity of about 1%
- Detection of surface sub-millimetric defects and scratches with depth less than 0.1 mm

Work in progress

Development of magnetic sensor array to measure the magnetic field during the electropolishing process on non-planar geometry.

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