Development of Ho-123 Coated Conductors by PLD Method
- for HTS Power Cable -

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This work was supported by NEDO and Super-GM as Collaborative Research and Development of Fundamental Technology for Superconductivity applications.
Bi-2223 wires are widely applicable for various prototypes; cables, magnets, transformers, and FCLs

RE123 Coated Conductors are under development
HoBaCuO Coated Conductor

Coated Conductor for National program (SEI)
- Phase I (FY1999-FY2002) : HoBCO on ISD Substrate
- Phase II(FY2003-FY2007) : HoBCO on Textured Substrate

Milestones
- FY2005: 200A-200m
- FY2007: 300A-500m
- Tape Speed = 5m/H
- Cost = $8/Am
Deposition Process

- Simple Oxides (CeO2, YZS, etc.)
  - Thin Film (<1 Micron)
  - Multi Layered Structure
  - Wide Deposition Condition
  - Large Area & Low Cost

- RE-123 Oxides (HoBCO)
  - Thick Film (>1 Micron)
  - High Jc & Ic

- Conventional Large Area Deposition Process
  - RF Sputter
  - EB

- Special Deposition Process
  - PLD
PLD System for Long Wire

- Optical system
- Excimer laser
- Deposition chamber
- Winding or supply chamber
High Ic of HoBCO Layer

- Ic=357A/cmW (on single crystalline substrate)
- Ic=153A/cmW
- FWHM (CeO$_2$): 6～7 µm
- Ic=101A/cmW
- FWHM(CeO$_2$): 9～10 µm
High Rate Deposition of HoBCO

Deposition rate (µm/min) vs. Laser Power (W)

- HoBCO
- YBCO
Deterioration of Jc under temperature and humidity

Temperature 60°C
Humidity 70%

HoBCO

YBCO
Elementary study for HTS Power Cable Conductor

Several complex stress is adopted in assembling process

- Tension
- Compression by bending
- Spiral+Bending
- Spiral+bending+Tension
- Pressure

Simple Stress → Complex stress
Tensile Stress on Jc of HoBCO Coated Conductor

* N.Ayai: Advances in Superconductivity XII (1999), p631p
Bending Stress on Jc of HoBaCuO Coated Conductor

Method

Compressive bending strain

\[ \varepsilon(\%) = \frac{t}{D} \times 100 \]

- \( D \): diameter of bending
- \( t \): thickness of tape

Graph showing Jc/Jc0 at 77K for YBCO and HoBCO as a function of bending strain (%).
Spiral Bending Stress on Jc of HoBaCuO Coated Conductor

Spiral bending

Compressive spiral-bending stress

\[ \varepsilon(\%) = \frac{t}{D} \times \cos \theta \times 100 \]

\[ \theta = \tan^{-1}\left(\frac{P}{\pi D}\right) \]

- \( D \): diameter of bending
- \( t \): thickness of tape
- \( P \): pitch of winding

\[ \Delta \text{Jc/Jc}_0 \text{ at 77K} \]

- Former diameter:
  - 19.1mm
  - 14.7mm
  - 10.4mm
Jc vs Strain (Bending + Tension) of HoBaCuO Coated Conductor

\[ \text{Total tensile strain} = \text{Tensile strain} - \text{Bending strain} \]

(Total tensile strain = Tensile strain - Bending strain)
Self field analysis of 4-layer conductor

- φ19mm former, 15 tapes/layer, SSZZ, 3kA capacity
- Uniform current distribution by adjusting assembling pitch

Model

Result
Self Field Analysis of 4-Layer Conductor

Gap between tapes (mm)

Br (Tesla)

- 1st layer
- 2nd layer
- 3rd layer
- 4th layer

Br: Perpendicular to HoBCO tape surface

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AC loss Calculation of 4-layer Conductor by Self Field

Parallel to HoBCO tape surface (Bz, Bt)

\[
W = 2\mu_0 J_c dfH \left(1 - \frac{2}{3} \frac{J_c d}{H}\right) (H > J_{cd})
\]

\[
W = \frac{2}{3} \mu_0 f \frac{H}{J_c d} (H \ll J_{cd})
\]

Perpendicular to HoBCO tape surface (Br)

\[
Q = \frac{4\mu_0 a}{S} \frac{J_c H}{g\left(\frac{H}{H_c}\right)}
\]

\[
g(x) = \frac{2}{x} \ln \cosh x - \tanh x
\]

3kA-single conductor: AC loss (gap:0mm) = 0.46W/m
AC loss (gap:0.6mm) = 0.36W/m
AC loss (gap:1.0mm) = 0.88W/m
## Assembling for Cable Conductor

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2-layer, 1m</td>
<td>4-layer, 1m</td>
<td>4-layer, 7m</td>
</tr>
<tr>
<td>(hand winding)</td>
<td>(hand winding)</td>
<td>(assembling machine)</td>
</tr>
<tr>
<td>SS,SZ spiral</td>
<td>SZSZ spiral</td>
<td>SSZZ spiral</td>
</tr>
</tbody>
</table>

- **HoBCO tape**
- **dummy tape**
- **former**
- **All dummy tape**
### Parameter of 2-Layer Conductor

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cable</strong></td>
<td>Size : 19mm x 21mm</td>
</tr>
<tr>
<td></td>
<td>Former : Cu pipe</td>
</tr>
<tr>
<td></td>
<td>Structure : 2 layer</td>
</tr>
<tr>
<td></td>
<td>Length : 1m</td>
</tr>
<tr>
<td></td>
<td>Spiral winding : SS, SZ</td>
</tr>
<tr>
<td></td>
<td>SC tape : 1</td>
</tr>
<tr>
<td></td>
<td><em>(HoBCO layer is compressive)</em></td>
</tr>
<tr>
<td></td>
<td>Dummy tape : 14</td>
</tr>
<tr>
<td><strong>HoBCO tape</strong></td>
<td>Size : 4mm x 0.08mm</td>
</tr>
<tr>
<td></td>
<td>Substrate : Hastelloy</td>
</tr>
<tr>
<td></td>
<td>Buffer : YSZ</td>
</tr>
<tr>
<td></td>
<td>Jc : $10^5$A/cm$^2$ (77K, 0T)</td>
</tr>
</tbody>
</table>

![SS](image1.png)

![SZ](image2.png)
Bending Properties of 2-Layer Conductor

- Liquid nitrogen measurement
- Voltage probe
- Conductor

Graph:
- Jc/Jc0 at 77K
- R=1200mm, 950mm, 750mm, 550mm, 370mm
- SS 1st layer
- SS 2nd layer
- SZ 1st layer
- SZ 2nd layer

Bending strain (%)

R=1200mm, 950mm, 750mm, 550mm, 370mm
## Parameter of 4-Layer Conductor

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<tr>
<td><strong>Cable</strong></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>19mm x 21mm x 1m</td>
</tr>
<tr>
<td>Former</td>
<td>Cu pipe</td>
</tr>
<tr>
<td>Structure</td>
<td>4 layer, SZSZ winding</td>
</tr>
<tr>
<td>SC tape</td>
<td>1 (HoBCO layer is compressive)</td>
</tr>
<tr>
<td>Dummy tape</td>
<td>14</td>
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<tr>
<td><strong>HoBCO tape</strong></td>
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<td>Hastelloy</td>
</tr>
<tr>
<td>Jc</td>
<td>$10^5$A/cm² (77K,0T)</td>
</tr>
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![Diagram of 4-Layer Conductor](image)
Bending properties of 4-Layer Conductor

![Graph showing the bending properties of a 4-layer conductor at 77K, with different layers labeled and data points indicating the Jc/Ic ratio as a function of 1/R (mm⁻¹).]
4-Layer, 7m Cable Conductor

Conductor with dummy tape by using assembling machine

<table>
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<tbody>
<tr>
<td>Tape      : 4mm x 0.08mm hastelloy</td>
</tr>
<tr>
<td>Former    : Cu stranded flexible cable</td>
</tr>
<tr>
<td>Strand number : 15 for each layer</td>
</tr>
<tr>
<td>1\textsuperscript{st} layer : OD=19.5mm, Pitch=300mm, S</td>
</tr>
<tr>
<td>2\textsuperscript{nd} layer : OD=19.9mm, Pitch=470mm, S</td>
</tr>
<tr>
<td>3\textsuperscript{rd} layer : OD=20.9mm, Pitch=380mm, Z</td>
</tr>
<tr>
<td>4\textsuperscript{th} layer : OD=21.4mm, Pitch=170mm, Z</td>
</tr>
</tbody>
</table>
Distribution of Diameter and Pitch

- Diameter (mm): 19.5, 20, 20.5, 21, 21.5, 22, 22.5, 23
- Pitch (mm): 150, 200, 250, 300, 350, 400, 450, 500

- No. 1 Layer
- No. 2 Layer
- No. 3 Layer
- No. 4 Layer

Graphs showing distribution of diameter and pitch across different layers.
Several Bi-based HTS Cable Demonstrations in the world (EU, US, Japan, Korea, China, etc.) were successfully implemented.

RE-123 (HoBCO) coated conductor has been in progress rapidly.

HTS Cables with Large Transmission Capacity and Low AC Loss are Indispensable for 21st Century’s Power Grid.