Performance and Quality Improvements in SuperPower 2G HTS Wires

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Director of R&D, SuperPower Inc.

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July 14-19, 2013  ■  Boston, MA
Outline

- Market & technology requirements for 2G HTS wires
- In-field performance for coil & magnet applications
- “Advanced Pinning” structure
- Performance in production
- Roadmap to further performance enhancements
- Quality & uniformity
- Engineering for robust wire design
- Conclusion

SuperPower team:
Hisaki Sakamoto, Allan Knoll, Ross McClure, Gene Carota, Karol Zdun, Sungjin Kim, Yifei Zhang, Drew Hazelton, Yimin Chen, Changhui Lei, Albert Guevara, Honghai Song, Paul Brownsey, Trudy Lehner
SuperPower’s ReBCO superconductor with artificial pinning structure

MOCVD grown ReBCO layer + BaZrO (BZO) nanorods
  Flux pinning sites for high in-field $I_c$
Buffer layers with IBAD-MgO
  Diffusion barrier to metal substrate
  Ideal lattice matching from substrate through ReBCO
Hastelloy® substrate
  Light, thin, high-tension resistivity
SuperPower addresses a wide range of application areas, each with different requirements.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>• FCL</td>
<td>• Motors</td>
<td>• Maglev</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td>• HF magnets</td>
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<tr>
<td>• Cable</td>
<td>• Cables</td>
<td>• EV Motors</td>
<td>• Motors</td>
<td>• NMR</td>
<td>• Space exploration</td>
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<tr>
<td>• Generators</td>
<td>• Directed energy weapons</td>
<td>• Rail engines</td>
<td>• Generators</td>
<td>• MRI</td>
<td>• SQUIDS</td>
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<tr>
<td>• Transformers, incl. FCL</td>
<td></td>
<td>• Rail transformers</td>
<td>• Magnetic separation</td>
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<td>• High energy physics</td>
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<tr>
<td>• Storage</td>
<td></td>
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<td>• Bearings</td>
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<td>• Electronics</td>
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<tr>
<td>– SMES</td>
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<td>• Cell tower base station filters</td>
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<td>– Flywheels</td>
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Courtesy of SuperPower and Furukawa

Courtesy of Waukesha

Courtesy of Oswald
## Technical requirements by applications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Stationary or linear</th>
<th>Dynamic or rotary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applications</strong></td>
<td>Power cable, FCL, maglev, linear-guide, etc.</td>
<td>Motor, generator, SMES, ultra-high field magnet</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>LN$_2$ (77K, 65K, 50K)</td>
<td>Circulated He-gas (30-40K) Liquid He (4.2K)</td>
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<tr>
<td><strong>Field intensity</strong></td>
<td>Weak (0T or self)</td>
<td>Strong (2T, 5T, 20T, 30T)</td>
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<tr>
<td><strong>Field component</strong></td>
<td>Parallel to tape surface</td>
<td><strong>Perpendicular</strong> to tape surface</td>
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<tr>
<td><strong>Mechanical</strong></td>
<td>Self tension Moderate thermal stress</td>
<td><strong>Large</strong> hoop stress &amp; thermal contraction</td>
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</table>
Operating conditions vary by application

Lift Factor defined as

\[ \frac{I_c(B,T)}{I_c(\text{self field, 77K})} \]

Applied Field \( B \) (T)
# Engineering progresses

<table>
<thead>
<tr>
<th>Feature</th>
<th>Approach</th>
<th>Assessment</th>
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<tbody>
<tr>
<td><strong>In-field performance</strong></td>
<td>Flux pinning with engineered nanostructure</td>
<td>Enhanced $I_c$ at low (30-40K) temp. and under perpendicular field components (2-5T)</td>
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<tr>
<td><strong>Critical current ($I_c$)</strong></td>
<td>Consistent &amp; uniform process</td>
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<td>under magnetic field</td>
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<td><strong>Robust wire design</strong></td>
<td>“Hastelloy” based substrate supporting structure</td>
<td>Tensile strength</td>
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<td><strong>Mechanical testing</strong></td>
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<td>Peel strength</td>
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<td>Splicing stress</td>
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<tr>
<td><strong>Coil-demonstration</strong></td>
<td>Coil-winding technology; Forming, molding, co-winding material</td>
<td>High field (20T-30T) and low temp (4.2K)</td>
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<td><strong>This talk:</strong></td>
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<td>Status and progress for in-field performances</td>
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<td></td>
<td>Evaluation of mechanical strength</td>
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**Related talk for coil-application & design (5OrAB-04):**

“Engineering Design, Fabrication and Protection Considerations for 2G HTS High Field Coils”
SuperPower’s ReBCO superconductor with superior in-field performance by “engineered” flux-pinning structure

MOCVD grown ReBCO layer + BaZrO (BZO) nanorods
Flux pinning structure for high in-field $I_c$
In-field performance:
Advantage of 2G HTS wire with flux pinning

Advanced MOCVD growth technology:
• Formation of dense & uniform nanorods
• Engineered growth properties
• Potential migration to new compositions

→ Enhanced Artificial Pinning Effect
→ Improved in-field critical current
→ SuperPower’s “AP wire” recipe
Increased Zr doping in ReBCO layer for improvement in critical current in the field

Control keys in production for AP wires:
Optimum growth conditions for effective flux-pinning

Superconductivity  Pinning effect  (BZO formation)

Optimum window for enhanced recipe (more BZO)
Optimum window for present recipe (less BZO)

Growth conditions
Precursor composition / Flow rate / Concentration / Chamber pressure, etc. etc.
Key examples: Effects of RE composition

15%-Zr doped GdYBCO:

- Composition of “Gd+Y” was experimented with in variations of 1.1, 1.2, 1.3, and 1.5.
- TEM cross-sections were compared in terms of continuous & consistent formation of BZO nano-rods.
Rare earth (Gd+Y) composition vs. critical current

15%-Zr doped GdYBCO:

@ 77K / 0T or 1T;
  • Critical current (Ic) is less dependent on (Gd+Y) composition
  • ab-peak enhanced, c-peak suppressed with increasing (Gd+Y)

@ 40K / 3T;
  • Ic is maximized at (Gd+Y) = 1.2, indicating strongest flux pinning
Process consistency & repeatability

Reproducible In-field Ic (30K/3T) performances at all 3 locations;
Research in UH • Production in SuperPower • Pilot-system in UH/SP joint project

30K/2.5T, 12mm-w tape

Research MOCVD (UH)
- ASC12
- ISS11

SP Production MOCVD (AP-model)

Present AP model (Zr=7.5%)
- 800A - 1000A@30K/2.5T, 12mm-w

UH-SP Pilot MOCVD
- (AP-model as “baseline”)

Measurement performed by
- UNIVERSITY of HOUSTON
- ToSUH
Roadmap to enhance in-field $I_c$

- Present AP model (800A - 1000A)
- Enhanced BZO
- Enhanced AP plan (1500A)
- Next-gen. (3000A)
- Advanced engineering of nanostructure

30K/2.5T, 12mm-w tape

- 3000A
- 2000A
- 1000A

- '13
- '14
- '15
- '16
- 2018

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MT-23 Boston, MA July 14-19, 2013
$I_c$ uniformity along length (TapeStar)

- Magnetic, non-contact measurement
- High spacial resolution, high speed, reel-to-reel
- Monitoring $I_c$ at multiple production points after MOCVD
- Capability of quantitative 2D uniformity inspection
$I_c$ uniformity along length
(four-probe transport measurement)
SuperPower’s ReBCO superconductor with superior mechanical robustness & compactness

Hastelloy® substrate & compact Cu-plated design
Light, thin, high-tension resistivity
Tensile strength predominately determined by substrate

Tensile stress-strain relationship of as-polished Hastelloy substrate (room temperature)

Tensile stress-strain relationship of SCS4050 wires with different Cu stabilizer thickness (room temperature)
Delamination strength studied with peel test

90° peel test

T-peel test

Relationship between peel strength and processing conditions established
Reliable splices – low resistance and high strength

- Splicing always required by real applications
- Splice properties are important conductor performance and have influences on dielectrics and cryogenics as well
- Low resistance and high electromechanical strength are basic requirements

- Contact resistivity at REBCO/Ag interface has an effect on splice resistance
- Splices fabricated via soldering at a temperature below 250°C
- Soldering temperature, pressure, duration time are important parameters
- $I_c$ retained across splices with no degradation through soldering
- Splice resistance $R \leq 20 \, \text{n}\Omega$ for the lap joint geometry with a 10cm overlap length
- Splicing per customer request and each splice inspected
5OrAB. Superconducting High Field Magnets II

“Engineering Design, Fabrication and Protection Considerations for 2G HTS High Field Coils”

Honghai Song, Paul Brownsey, J. Waterman, Yifei Zhang,
Toru Fukushima, Drew Hazelton

- 2G HTS coil winding for double pancake design
- Coil stress analysis
- Engineering design with in-field $I_c(B, T, \Phi)$ characterization
- Terminal leads and joints, insulation and epoxy
Conclusions

- Recent progress in production was described for in-field performance of 2G HTS wires
- Consistent & reproducible Ic @30K / 2.5T for motor, generator, and coil applications
- Product quality & uniformity
- Mechanical stability & reliability demonstrated
- 2G HTS wires with further enhancement of in-field performance aimed at next generation devices
Thank You!

The authors would like to thank Professor Venkat Selvamanickam, Dr. Aixia Xu, and Mr. Masayasu Kasahara of University of Houston, for the research in MOCVD growth, in-field measurement, and material-analysis.

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