superior performance. powerful technology.

2G HTS Conductors at SuperPower

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Low Temperature High Field Superconductor Workshop 2012 (LTHFSWS2012)
Napa, CA ▪ November 6, 2012
From GE to Furukawa

• History
  – 1971: Superconductivity group spins out of General Electric and forms Intermagnetics General Corporation
  – 1987: following the 1986 discovery by Bednorz and Mueller, Intermagnetics forms a dedicated group to work on HTS
  – 2000: Intermagnetics forms SuperPower to develop 2G HTS technology for Energy Technology applications
  – 2006: Intermagnetics is acquired by Royal Philips Electronics for MRI magnet business
    • Holds SuperPower to build value
  – 2012: SuperPower is acquired by Furukawa Electric Co., Ltd.
Furukawa Electric Co., Ltd.

Founded: 1884

Net sales: ¥918,808 million (Consolidated) 3/31/12

Employees: 45,000

Head Office: Chiyodaku, Tokyo - Japan

Factories: 7
- Chiba, Nikko, Hiratsuka, Mie, Yokohama,
- Copper Tube Division and Copper Foil Division

Branch and Sales Offices: 10

Research Laboratories: 7
- Yokohama R&D Laboratories
- Metal Research Center
- Ecology & Electronics Laboratories
- Power & System Laboratories
- FITEL Photonics Laboratory
- R&D Center for Automotive Systems & Devices
- HTS Project Team

LTHFSW 2012 – Napa, CA – November 6, 2012
FEC Businesses

Three core materials across five business segments

- Metals
- Photonics
- Metal Polymer
- Telecommunications
- Energy/Industrial Products:

FURUKAWA ELECTRIC
SuperPower® 2G HTS wire: Thin film deposition on robust, flexible substrate

- Automated processes
- Reel-to-reel systems
- High throughput, fast processes

- Modular and scaleable systems
- Quality assurance throughout
- Rigorous testing, product certification with each delivery
Each layer serves a function….

• Substrate (Hastelloy® C-276) provides mechanical strength, electropolished base for subsequent layer growth

• Buffer stack provides:
  – Diffusion barrier between substrate and superconductor
  – IBAD MgO layer provides texture template for growing aligned superconductor, necessary for high current density
  – Final buffer layer provides lattice match between buffer stack and superconductor

• HTS superconductor layer – (RE)BCO superconductor with BZO based pinning sites for high current carrying capability in background magnetic field.

• Ag layer – provides good current transfer to HTS layer while providing ready path oxygen diffusion during final anneal.

• Cu layer – provides stabilization(parallel path) during operation and quench conditions.
2G HTS Wire Specifications

- Robust, high-performance wire; several architectures, incl. variations of width, substrate thickness, stabilizer, and insulation
  - Insulated wire: Kapton wrapped - 30% overlap or butt-wrap available
- Two chemical formulations:
  - AP (Advanced Pinning) – for enhanced in-field performance in motors, generators, transformers, SMES, high field magnets, etc.
  - CF (Cable Formulation) – for cable or FCL
2G HTS offers excellent performance for all electrical device operating ranges

Normalized $I_c$ vs. Applied Field $B / c$

- 4.2 K
- 14 K
- 22 K
- 33 K
- 45 K
- 50 K
- 65 K
- 77 K

- Motors, generators
- SMES
- Cables, FCLs, transformers
Critical current vs. temperature and magnetic field of recent AP production material
SuperPower 2G HTS wire has high tensile strength.
SuperPower 2G HTS wire exhibits good fatigue strength

- $I_c$ & $N$ do not change under fatigue cycling if stress amplitude is below $S_{IcRL}$
- For stress $> S_{IcRL}$, $I_c$ & $N$ degrade with fatigue cycles
- Recommend a 98% reversible $I_c$ retention as “failure” criterion

Data from Ron Holtz, NRL
SuperPower is driving price down on two fronts: Improving manufacturing process and increasing in-field performance.

<table>
<thead>
<tr>
<th>Time</th>
<th>Performance at 77 K, zero field*</th>
<th>Lift Factor at device operating condition (30K, 2T)</th>
<th>Performance at device operating condition</th>
<th>Wire price ($/m)</th>
<th>Wire price ($/kA-m) at device operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>100 A</td>
<td>2</td>
<td>200 A</td>
<td>$ 45</td>
<td>$225</td>
</tr>
<tr>
<td>2 years</td>
<td>150 A</td>
<td>4</td>
<td>600 A</td>
<td>$ 40</td>
<td>$ 67</td>
</tr>
<tr>
<td>4 years</td>
<td>200 A</td>
<td>6</td>
<td>1200 A</td>
<td>$ 35</td>
<td>$ 30</td>
</tr>
</tbody>
</table>

* Based 4mm width

**Improving wire performance is key to success**
Strong history of price improvements achieved through technology advancements

- 10 m demo
- 100 m demo
- First year of pilot production
- 500 m demo
- 1,000 m demo
- 2 to 4x higher throughput
- R&D partnership with UH
- AP wire (Zr-doped) product introduction

- 77 K, self field
- 30 K, 2 T

Price ($/kA-m)

Year

- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
Moving toward large-scale production of robust, high-performance wire

• High critical current:
  – 100A standard; 110-120+ A premium (4 mm width)
• Uniform critical current over long lengths: +/- 10% standard deviation
• Single piece lengths of 50-300 m (without splices); up to 1 km and longer with high quality splices
• Excellent joints & solderability:
  – No degradation in Ic even when joint is bent over 1” diameter and thermal cycled
  – Joint resistance ~ 40 nohm-cm^2
  – No issues with soldering to our 2G HTS Wire
• Manufacturing volume steadily increasing
2G HTS has been used in multiple high field insert coil demonstrations

SuperPower: 26.8 T, 27.4 T / 20 T
NHMFL: 33.8 T, 35.4 T / 31 T
BNL: various HF coils to 16 T (500 A/mm²)

Layer wound 2G insert for commercial customer

SP 26.8T
NHMFL 35.4T
BNL 2G HTS Coil
R&D Area: Advanced pinning continues to progress

Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

5 nm sized, few hundred nanometer long BZO nanocolumns with ~35 nm spacing created during in situ MOCVD process with 7.5% Zr
Significant improvement in lift factor at targeted operating conditions demonstrated
R&D topic: Multifilamentary 2G HTS tapes for low ac loss applications

- Filamentization of 2G HTS tapes is desired for low ac loss applications.
- Techniques for tape striation demonstrated
- But scale-up to a cost-effective, robust manufacturing process continues

<table>
<thead>
<tr>
<th>Filament</th>
<th>Width</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-filament</td>
<td>4 mm</td>
<td>up to 15 m</td>
</tr>
<tr>
<td>32-filament</td>
<td>4 mm</td>
<td>difficult to make even 1 m lengths</td>
</tr>
</tbody>
</table>

Graph showing ac loss vs. B_{ac rms} (T) at 100 Hz with unstriated and multifilamentary samples.
R&D topic: Alternative configurations for compact high amperage windings demonstrated

- Compact cable - ACT

- ROEBEL cable – IRL, KIT

- Bonded conductors for kA class conductors
Questions?

Thank you for your interest!

For further information about SuperPower,
please visit us at:  www.superpower-inc.com

or e-mail:  info@superpower-inc.com