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2015 Technology and Manufacturing Innovations at SuperPower
Outline

• Super Power (SP) history & background
• General structure of 2G HTS
• Electrical properties (Ic vs. B & T)
• Insulation
• Mechanical properties
• New initiatives
  – 15% Zr additions
  – 30µm substrates
  – In-situ insulation
• Applications case studies
• Pricing and delivery
One Furukawa: offering both LTS and HTS solutions

Three core materials across five business segments

CORPORATE PHILOSOPHY
Drawing on more than a century of expertise in the development and fabrication of advanced materials, we will contribute to the realization of a sustainable society through continuous technological innovation.
Furukawa has a long history in LTS

CUSTOMIZATION
Various conductor designs satisfy customer demands

HIGH TECHNOLOGY
Sophisticated metal composite technology

HIGH QUALITY
High-precision cabling technology

NbTi wire with various Cu ratio & filament sizes
Low ac loss NbTi wire
Al-stabilized NbTi wire
High Jc Nb3Sn wire
High strength Nb3Sn wire
Al-stabilized NbTi Rutherford cable
NbTi Rutherford cable with cored bar
NbTi Rutherford cable with high-precision
SuperPower’s history as a 2G HTS industry leader

- **2000-2006**: The Intermagnetics Years
  - SuperPower formed from the Technology Development Organization of Intermagnetics
  - 2G HTS technology development
  - Production scale-up
  - Demonstration projects – energy focus

- **2006-2012**: The Philips Years
  - Transition from scale-up to commercialization
  - Exploration of a wide range of commercial markets
  - Buildup of a broad customer base

- **From 2012 onward**: The Furukawa Years
  - Continuous manufacturing improvements over established baseline capabilities … to address market needs
  - Steady expansion of production to meet market requirements
  - Focus on long-term sustainability in a slowly evolving market
2G HTS wire has been produced at the manufacturing facility since 2006

Substrate Electropolishing

MOCVD

IBAD

Buffer Sputtering
Technology benefits for our customers today

- **High $I_c$:** $>450A$ standard (12 mm width; 77K, 0T)
- **Uniform $I_c$ over long lengths:** STDEV +/- 10%
  - Good, repeatable bandwidth
  - Good 2D uniformity (across width)
- **High engineering current density:**
  - Very thin substrates and stabilizers
- **Chemistry:**
  - Currently two formulations
    - AP (Advanced Pinning) – enhanced performance for in-magnetic field applications
    - CF (Cable Formulation) – 77K, low fields (cable, FCL, transformer)
- **Flexible, robust architecture:**
  - Multiple widths and thicknesses (substrate, stabilizers)
- **Superior mechanical properties:**
  - Yield strength 550 MPa and higher with superalloy-based coated conductors
  - Excellent joints and solderability
SuperPower’s (RE)BCO superconductor with artificial pinning structure provides a solution for demanding applications

- Hastelloy® C276 substrate
  - high strength
  - high resistance
  - non-magnetic
- Buffer layers with IBAD-MgO
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through REBCO
- MOCVD grown (RE)BCO layer with BZO nanorods
  - Flux pinning sites for high in-field $I_c$
  - Silver and copper stabilization
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 oxygen diffusion path during final anneal
- **Cu layer** – provides stabilization (parallel path) during operation and quench conditions
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IcBT improvements
Recent step wise improvements to meet market challenges

- **Critical current**
  - Recent advances in processing have significantly increased the base $I_c$ (77K, sf) of SP 2G HTS tapes into the 400-600 A/cm-w range

- **Piece length**
  - Recent advances in processing have also increased the stable production piece length of SP 2G HTS tapes >500m

- **Current density**
  - SP 2G HTS tapes have the highest conductor Jc’s in the industry
  - New initiatives will maintain this performance advantage
    - Thinner substrates (>30% Jc improvements)
    - Improved lift factors (2x +) with enhanced pinning

- **Pricing**
  - Improved yields improve costs
  - Review of pricing structure to facilitate competitive pricing
Critical current vs. field: standard 7.5% Zr AP

Measurements made at Tohoku University
Lift factor vs. field: standard 7.5% Zr AP

Measurements made at Tohoku University
Critical current vs. field: enhanced 7.5% Zr AP

Measurements made at Tohoku University
Lift factor vs. field: enhanced 7.5% Zr AP

Measurements made at Tohoku University
Critical current comparison: standard vs. enhanced

Measurements made at Tohoku University
Lift factor comparison: standard vs. enhanced

Measurements made at Tohoku University
IcBT typical data

M4-292-9S 2mm

-30  -10   10   30   50   70   90  110

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<tr>
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<tr>
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<td>400</td>
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<tr>
<td>500</td>
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<td>600</td>
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- | 77K/1.5T |
- | 65K/1.5T |
- | 50K/1.5T |
- | 40K/1.5T |
- | 30K/1.5T |
- | 20K/1.5T |

Ic [A]

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2015 SuperPower Update
IcBT vs. angle

![Graph showing IcBT vs. angle for M4-287-6E with various fields and angles.](image)
$I_c$ uniformity along length (TapeStar)

Position (m) (on a 12 mm wide wire)

- Magnetic, non-contact measurement
- High spacial resolution ($?? \text{ mm}$), high speed, reel-to-reel
- Monitoring $I_c$ at multiple production points after MOCVD
- Capable of quantitative 2D uniformity inspection
Good 2D uniformity achieved across the width!

Mechanical properties
Comprehensive testing capabilities for mechanical and electromechanical properties

- Axial tensile test at room temperature or at 77K (with $I_c$)
  - Measurement of elastic modulus and yield stress
  - Determination of critical stress and irreversible stress (strain)
- Measurement of delamination strength – various testing methods
  - Peel test: at room temperature and with varying peeling angle
  - Pin-pull (c-axis tensile) test: at room temperature
  - Anvil (c-axis tensile) test: at room temperature or at 77K (with $I_c$)
- Transverse (c-axis) compressive test at 77K (with $I_c$)
  - Measurement of critical compressive stress
- Torsion-tension test at 77K (with $I_c$)
  - Measurement of critical tensile stress under twist
Studies on mechanical/electromechanical properties

- Mechanical behaviors under various stress conditions at RT and/or 77K
- Electromechanical testing for stress (strain) dependence of $I_c$ at 77K
- Electromechanical strength determined by critical stress with 95% $I_c$ retention

Fixtures for mechanical/electromechanical testing:
- Axial tensile
  - RT or 77K w/ $I_c$
- Transverse tensile
  - Stud method
  - RT or 77K w/ $I_c$

Normalized $I_c$ vs. axial tensile stress for:
- SF12100
- SCS12050-20
- SCS12050-40
- SCS12050-100
- FtF-Bonded

Axial Tensile Stress (MPa)

Normalized $I_c$ vs. axial tensile stress for

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2015 SuperPower Update
Studies on mechanical/electromechanical properties

90° Peel test, RT

Transverse tensile
Pin-pull method
RT

Transverse tensile
Anvil method
RT or 77K

Weibull analysis results – anvil test
Tensile property of wire without stabilizer

- Tensile stress-strain relationship (RT & 77K) and $I_c$ vs. tensile stress relationship (77K) measured on tape without Ag and Cu (processed up to (RE)BCO only. Hastelloy substrate thickness = 50 µm)
- $\sigma_{c,0.95} \approx 800$ MPa, $\varepsilon_{c,0.95} \approx 0.45\%$
Tensile property of various wires

- Tensile stress-strain relationship measured at RT and 77K
Tensile property of various wires

- \( I_c \) vs. tensile stress relationship at 77K

For wires on 50\(\mu\)m Hastelloy Substrate
Tensile property of various wires

- $I_c$ vs. tensile strain relationship at 77K
Effect of Cu/Substrate thickness ratio on $\sigma_{c,0.95}$

- Comparison of four wires on 50 $\mu$m thick substrate
- $E_{0.45}$, which is the chord modulus in between 0% and 0.45% strain, depends on Cu/substrate thickness ratio
- While $\varepsilon_{c,0.95}$ is a constant of about 0.45%, $\sigma_{c,0.95}$ depends on $E_{0.45}$
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New initiatives
New Initiatives being transitioned from R&D to production

- 15% Zr additions
- 30 micron substrate
- Bonded tapes
- Insulation options
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15% Zr additions
TEM analysis for enhanced Zr doping

Zr = 7.5%
Size: 4.4~6.2nm
Distance: 20.8~26.8nm

Zr = 11.5%
Size: 4.4~5.6nm
Distance: 16~20.7nm

Zr = 15%
Size: 4.4~5.6nm
Distance: 12.8~18.3nm
Trend of BZO rod

- The BZO rod size is almost in the same range
- Distance of BZO rods decreases with increasing Zr doping ratio
$I_c$ performance with Zr = 15% at 50K

- Enhanced Zr doping samples promise high $I_c$ performance
In-field performance at 30K/2T

- Enhanced Zr doping samples promise high $I_c$ performance
Ic-B performance at various temperature

- Zr enhanced sample show high $I_c$ performance under 50K
$I_c$ performance vs. axial position on tape with $Zr = 15%$

- 130m length with $Zr = 15%$
- $I_c \sim 400A$ at 77K/sf
Long tapes with Zr = 15%

- Further work is underway before official release of Zr enhanced wires
  - Repeatability of $I_c$ performance at 20~50K and 2T thru 5T
  - Dispersion of $I_c$ performance
  - Mechanical property
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30 micron substrate
Improved \( J_e \) (engineering current density) wire with thinner substrate

- Existing products based on either 50 or 100 µm Hastelloy\textsuperscript{®} substrate
- For wire with 50 µm substrate and 40 µm Cu, the total thickness is ~ 0.095 mm
- Wires with thinner substrates (38, 30 and 25 µm) are being developed
- For standard Cu thickness of 40 µm total on a 30 µm Hastelloy\textsuperscript{®} substrate, conductor thickness is reduced to ~75 µm
- This implies a 27\% increase in engineering current density (\( J_e \))

![Graph showing Normalized \( J_e \) for different Hastelloy Substrate Thicknesses and Cu thicknesses](image_url)

Baseline wire is on 50µm substrate and with 40µm Cu
Tensile testing of thinner substrate

- RT tensile testing of 1.2mil (30µm) thick substrate
- Yield stress ($\sigma_{0.2}$) and elastic modulus (E) measured and compared with 2.0mil (50µm) thick substrate

### Vendor Specification Properties

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<th>Substrate</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>E (GPa)</th>
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<tr>
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### Measured Properties

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</table>
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Bonded tapes
Bonded tapes tailored for various applications

- Bonded tape provide benefits with higher $I_c$, higher mechanical strength, tailored normal state resistivity, and/or improved stability
- A fully automated system has been built for fabrication of multiple tape bonded wire
- Variation in architecture – material and number of tapes, orientation
Examples:

- One 2G tape bonded with one CuNi alloy tape (up to 1 mm thick) – conductor with high mechanical strength and tailored normal state resistivity for FCL transformer
Examples (continued)

- Two 2G tapes bonded with one Cu tape in-between – conductor with high $I_c$ and improved stability for accelerator magnets

E-I characteristics (77K, sf) of a composite wire bonded with two 2G tapes with one Cu tape in-between
SP 2G HTS is used in several cable configurations

**Roebel Cable**
- Fabricated by winding mechanically punctured meandering tapes – high $I_c$ (~nkA) and low AC loss
- Uniformity across width and mechanical strength

W. Goldacker et al, IEEE TAS, 17(2007)3398

**CORC (Conductor on Round Core) Cable**
- Fabricated by winding multiple wires in a helical way around a small former – high $I_c$ (~nkA)
- High Je and mechanical strength

D C van der Laan et al, SUST, 24(2011)042001

**Twisted Stacked-Tape Cable (TSTC)**
- Fabricated by stacking multiple tapes together and twisting at a pitch length – high $I_c$ (~nkA)
- Mechanical strength

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Insulation options
New 2G HTS conductor insulations are being developed to meet customer requests

- Current option is a wrapped Kapton®/Polyimide insulation
  - Either overlapped (30-50%) or butt wrapped
  - 12.7 to 25.4 µm thick with 15 µm adhesive

- Evaluating Polyimide Electro-Deposited Conductor [PIED], developed by RIKEN, as alternative insulation
  - Thicknesses of 20 µm and below are being evaluated
  - Epoxied coils tested to date using this insulation show excellent results & resistance to delamination
High voltage tape insulation for robust bonded conductor available

Multiple wrapped layers of PPLP or equivalent insulation on 2G HTS bonded conductors available for high voltage applications
Offering improved services to our customers

• Up to 50% price reduction and delivery lead time compared 2013/2014 depending on application
• Upgraded *Quick Ship* list with greater variety
• Longer piece lengths, higher $I_c$ & greater product varieties