REBCO HTS Wire Manufacturing and Continuous Development at SuperPower

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Outline

• Introduction to SuperPower Inc.
• REBCO wire and its manufacturing
• Applications of REBCO wire
• Performance and quality of REBCO wire
• Development and challenges
• Summary
Introduction to SuperPower


- Formed in 2000
- Location: Schenectady, New York
- Number of employees: 30
- President & CEO: Dr. Toru Fukushima
- Product: REBCO 2G HTS wire
- A subsidiary of Furukawa Electric Co. Ltd. Since 2012
A brief history of SuperPower

• **2000-2006: The Intermagnetics Years**
  – SuperPower formed under IGC (Intermagnetics General Corporation)
  – 2G HTS wire technology research & development
  – Demonstration projects – electric power applications

• **2006-2012: The Philips Years**
  – Production scale-up
  – Market exploration
  – Performance improvements, flux pinning enhancement

• **From 2012 onward: The Furukawa Years**
  – Steady expansion of production capacity
  – Continuous performance improvements
  – Continuous R&D, customization
  – Processing optimization for quality and yield enhancement
Furukawa has a long history in LTS

- Nb-Ti wire with various Cu ratio & filament sizes
- Low ac loss Nb-Ti wire
- Al-stabilized Nb-Ti wire
- High Jc Nb₃Sn wire
- High strength Nb₃Sn wire
- Al-stabilized Nb-Ti Rutherford cable
- Nb-Ti Rutherford cable with cored bar
- Nb-Ti Rutherford cable with high-precision
REBCO wire manufacturing at SuperPower

Electropolishing

IBAD

Buffer Deposition

MOCVD

Electroplating

IBAD-MOCVD based technologies
# REBCO wire – basic information

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>REBa$_2$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>RE=Rear Earth</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>(1), 2, 3, 4, 6, 12</td>
<td></td>
</tr>
<tr>
<td>Substrate Thickness (µm)</td>
<td>30, 50, 100</td>
<td>Hastelloy</td>
</tr>
<tr>
<td>Ag Thickness (µm)</td>
<td>1~5</td>
<td>Sputtered</td>
</tr>
<tr>
<td>Cu Thickness (µm)</td>
<td>10~115 total</td>
<td>Electroplated</td>
</tr>
<tr>
<td>Insulation</td>
<td>Polyimide tape</td>
<td>Wrapped</td>
</tr>
<tr>
<td>Piece Length (m)</td>
<td>300~500</td>
<td></td>
</tr>
<tr>
<td>Joint resistance (nΩ)</td>
<td>&lt;20</td>
<td>Soldered</td>
</tr>
<tr>
<td>Ic(77K, s.f.) (A/12mm)</td>
<td>300~600</td>
<td>at 1µV/cm</td>
</tr>
<tr>
<td>σc,0.95 (MPa)</td>
<td>~550</td>
<td>$\gamma_s$ dependent</td>
</tr>
<tr>
<td>εc,0.95 (%)</td>
<td>~0.4</td>
<td></td>
</tr>
<tr>
<td>Min Bending D (mm)</td>
<td>5, 11, or 25</td>
<td>Substrate dependent</td>
</tr>
</tbody>
</table>

Cross-sectional image of a Cu-plated wire
# Targeted applications of REBCO HTS wires

<table>
<thead>
<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
</tr>
</thead>
</table>
| • Cables  
• FCLs  
• Generators  
• Transformers  
• SMES  
• Fusion Reactors | • Motors  
• Cables | • Maglev  
• Motors | • Induction Heaters  
• Motors  
• Generators  
• Magnetic Separation  
• Bearings | • MRI  
• Particle Therapy  
• Current Leads | • HF Magnets  
• NMR  
• Accelerators  
• Neutron and X-ray Scattering  
• Undulators |

![Cables](image1.png)  
![Motors](image2.png)  
![Maglev](image3.png)  
![Induction Heaters](image4.png)  
![MRI](image5.png)  
![HF Magnets](image6.png)
32T hybrid user magnet by NHMFL

**HTS/LTS hybrid magnet**

- LTS 15T
- HTS 17T
- Uniformity 1 cm DSV $5 \cdot 10^{-4}$
- Total inductance 254 H
- Stored energy 8.6 MJ
- Ramp to 32 T 1 hour
- Cycles 50,000

**HTS conductor**

- Wire width 4mm
- Wire thickness <0.170mm
- $I_c$ at 17T, 18°, 4.2K >256A
- $n$-value at 17T, 18°, 4.2K >25
- Stabilizer RRR >50
- $I_{op}$ 180A
1.3 GHz hybrid NMR by MIT

H800

- Top=4.2K, Iop=251A
- 3-nested-coil formation
- NI DP coils
- Tape width 6mm
- Tape total thickness 75µm
- Cu stabilizer 10µm per side
- Coil 1: 26 DP, 369MHz, 8.66T
- Coil 2: 32 DP, 242MHz, 5.68T
- Coil 3: 36 DP, 189MHz, 4.44T
- HTS contribution: 61.5% of 30.5T

Y. Iwasa
ARC fusion reactor – proposed by MIT (Affordable, Robust and Compact)

- HTS magnets at 9.2T on axis, 23T on coil
- Much smaller than ITER – 1/10\textsuperscript{th} the volume – same gain
- 5,000 tons
- 60,000 kAm of HTS
- Demountable joints for maintenance

9.2 T, 500MW, \( Q = 10 \)
Spherical fusion reactor by Tokamak Energy

ST25 (HTS)

ST40 (LN2 cooled Cu)

ST140 (HTS)
REBCO HTS high current cables

CORC® (Conductor on Round Core) Cable
- Fabricated by winding multiple wires in a helical way around a small round former
- High currents and current densities
- Mechanically strong
- Flexible
- High level of conductor transposition

First commercial sale (CERN)
- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

Courtesy of D. van der Laan, ACT LLC
Canted-Cosine-Theta magnets wound from CORC® wires

CORC® CCT magnet program goals
- Reach 5 T in CORC® CCT insert with 10 T (15 T) LTS CCT outsert
- Develop the CORC® CCT magnet technology in several steps
  - C1: 1 T 4.2 K, self-field, low-Je CORC® wire
  - C2: 4-5 T 4.2 K, self-field, 2-3 T in 10 T, high-Je CORC® wire
  - C3: 5 T in 15 T background, advanced CORC® wires

Courtesy of D. van der Laan, ACT LLC
REBCO HTS high current cables

Twisted Stacked-Tape Cable (TSTC)

32 YBCO tape Twisted Stacked-Tape Cable (TSTC) with 200 mm twist pitch

For example:

1. REBCO tapes are stacked between two thick copper strips.

2. The stacked-tapes with the copper strips are loosely wrapped with a fine stainless steel wire.

3. Then the stacked-tape cable is twisted.

Courtesy of M. Takayasu, MIT-PSFC
REBCO HTS high current cables

Twisted Stacked-Tape Cable (TSTC) Conductor Scale-up

TSTC basic conductors to fabricate multi-stage twisted cable.

Wrapped with copper foil

Soldered

30-tape (3 mm width) braided-sleeved soldered

TSTC conductor in a groove

Tapes in helical groove

By Supercon

CICC TSTC conductor

One channel cable

3 channel cable

40 YBCO tapes

20 YBCO tapes in each helical groove

Hex-cable CICC

Multiple-stage conductor

3x3 cable

3 x 6 CICC

12 sub-cable conductor

Courtesy of M. Takayasu, MIT-PSFC
REBCO HTS high current cables

Roebel Cable
- Fabricated by winding mechanically punctured meandering tapes
- High current and low AC loss

Stacked-tape Cable
- Two-step cabling
- 16 tapes per strand, twisted at 32 cm. 20 strands per cable, twisted at 100cm
- 60kA at 12T

Source: KIT

Nikolay Bykovsky et al, EUCAS 2017
Performance and quality of REBCO wire

- $I_c(B, T, \theta)$
  - Field dependence
  - Angular dependence
  - Minimum $I_c(\theta)$
  - Engineering current density, $J_e$
- Uniformity along length (piece length) and consistency
- Electromechanical properties (stress and strain limits)
  - Critical stress and strain
  - Irreversible stress and strain
  - Fatigue (in various stress states)
- Overcurrent stability
- Joint
  - Geometry
  - Resistance (resistivity)
  - Electromechanical strength (stress and strain limits)
- AC losses
- Insulation
In-field performance

$B$ (Tesla)

$I_c$ (A/4mm-w)

2013  2015  2017

4.2K, B//c
In-field performance – tailored structure

- Effect of Zr doping level on $I_c(BT\theta)$
  - 7.5%Zr, 15%Zr, or higher
  - Field, temperature and angular dependence
- Wire classification – optimized for various applications
  - High-temperature low-field
  - Intermediate-temperature intermediate-field
  - Low-temperature high-field

Cross-section, TEM, 7.5%Zr

Cross-section, TEM, 15%Zr
In-field performance – correlation

Earlier work at University of Houston suggested
- There is no correlation between $I_c(30K, 3T//c)$ and $I_c(77K, 0T)$
- There is a fairly good correlation between $I_c(30K, 3T//c)$ and $I_c(77K, 3T//c)$

In-field performance – correlation

Our recent data suggested
- There is a loosely inverse correlation between $I_c(4.2K, 5T//c)$ and $I_c(77K, 0T)$
- There is a fairly good correlation between $I_c(4.2K, 17T//c)$ and $I_c(4.2K, 5T//c)$
- There is a fairly good correlation between $I_c(4.2K, 8T//c)$ and $I_c(30K, 2T//c)$
Angular dependence and anisotropy

- Biaxially textured REBCO film is essentially highly anisotropic material – $I_c$ is dependent on magnetic field orientation
- The anisotropy is determined by the pinning landscape
- C-axis oriented BZO nano columns effectively enhance the pinning when $B//c$, therefore change the anisotropy
- The pinning effect from BZO is temperature and field dependent

$$I_c(B, \theta) = b_0 + F_n(b_k, \omega_k, \varphi_k; \theta), \quad b_k = b_k(B), \quad \omega_k = \omega_k(B).$$

Where

$$F_n(b_k, \omega_k, \varphi_k; \theta) = \sum_{k=1}^{n} b_k f_2(\omega_k, \theta - \varphi_k).$$

$$f_p(\omega, \theta) = \left[\omega^2 \cos^2(\theta) + \sin^2(\theta)\right]^{-1/p} = \frac{1}{[\omega e(\omega, \theta)]^{2/p}}, \quad p \in \{1, 2\}.$$

$I_c$ uniformity along length – magnetic measurement

Position (cm)(on a 4 mm wide wire)

- Non-contact measurement
- High spacial resolution, high speed, and reel-to-reel
- Monitoring $I_c$ at multiple production points after MOCVD
- Capable of quantitative 2D uniformity inspection
Ic uniformity along length – transport measurement

Ic (77K, s.f.) >160A, Piece length ~ 780m
Consistent in-field performance

![Graph showing Ic (A/4mm-w) vs. B//c (T) with data points made with M3 and M4.]
Higher $J_e$ (engineering current density) wire with thinner substrate

- Thinner substrates (30 µm or thinner) lead to higher $J_e$ without compromising the functionality of stabilizer that needs to be of certain thickness
- Higher $J_e$ and the flexibility of thinner wire facilitates fabrication of high current cables

A. Sundaram, et al, SUST, 29(2016)104007
Higher $J_e$ (engineering current density) wire with thinner substrate.

LBC3 HTS insert in 31T resistive magnet reached 45.46T.

Hahn, et al. EUCAS 2017
Mechanical and electromechanical properties and testing

- 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)
- Torsion-tension test at 77K (with $I_c$)
  - Measurement of critical tensile stress under twist
- Transverse ($c$-axis) compressive test at 77K (with $I_c$)
  - Measurement of critical compressive stress
- Bending test at 77K (with $I_c$)
  - Measurement of minimum bending diameter
- Measurement of delamination strength – various testing methods
  - Peel test: at room temperature
  - Pin-pull ($c$-axis tensile) test: at room temperature
  - Anvil ($c$-axis tensile) test: at room temperature or at 77K (with $I_c$)
Effect of stabilizer thickness ratio on critical stress under uniaxial tension

\[ \gamma_s = \frac{t_{(Ag+Cu)}}{t_{total}} \]
Continuous development and engineering

- **Wire on thinner substrates**
  - Higher engineering current density and enhanced mechanical flexibility
  - For fabrication of high current cables and high-field magnets
- **Different REBCO formula tailored for various operating conditions**
  - Intermediate-temperature (30-50K) and intermediate-field (2-4T) applications
  - Low-temperature (4.2K) high-field (>10T) applications
- **Bonded wires**
  - Enhanced performance and specific functionality
- **Wire filamentization**
  - Reduction of AC loss
  - Mitigation of screening effect
- **Alternative insulation**
  - Thinner and more uniform
- **Current Leads**
  - AgAu instead of pure Ag
- **Solder Coating**
  - Facilitate cabling
Summary

• In a longer term REBCO HTS wire holds a great promise for electric power, transportation and medical applications (high reliability required)

• REBCO HTS wire has the advantages over other superconducting wires and its Ic level is high enough for many high-field magnet applications

• Different types of high-current /low-AC-loss cables are being developed, which will facilitate the adoption of REBCO HTS wire for magnet applications

• Continuous development efforts are focused on
  – Further reduction in wire price and increase in wire production capacity
  – Further improvements in wire performance and quality
  – Technology advancements in AC loss reduction, joint and termination fabrication, insulation, quench detection/protection