Strong 2212 Wires

For advancing magnet performance

MEM 16 Workshop,
22 March, 2016
Tallahassee, FL

Solid Material Solutions, LLC
Alexander Otto (PhD)
Linda Saraco
Acknowledgements

- **Applied Superconductivity Center**
  Eric Hellstrom  Jianyi Jiang  David Larbalestier  Ulf Trociewitz  Mike Brown, Bob Walsh

- **Frances Bitter Magnet Laboratory**
  Julio Colque  Yuki Iwasa  John Voccio

- **nGimat**
  Stephen Johnson

- **Oxford Superconducting Systems**
  Kyle Damborsky  Yibing Huang

- **Solid Material Solutions**
  Julio Colque

- **Supramagnetics**
  Lesh Motowidlo

Portions of this work have been funded by
- Phase 2 SBIR DE-0011334
- The National High Magnetic Field Laboratory / Applied Superconductivity Center
- Solid Material Solutions, LLC
Strong, long, round and rectangular high Je 2212 wire (SRW)

In form and strength like Nb3Sn but can

operate at higher temperatures,

generate higher fields,

meet all requirements for it to be both useful and cost effective

for applications where it provides benefit over HTS tape, LTS wire
2212 SRW

Proof of concept

- Feasibility of approach, and materials
  for > 400 MPa with useful Je

Development

- Design meet all requirements
- Production individual process steps, then integrated
- Coiling and cabling basis wind & react focus, then react & wind
- Scale up to >50 m, then to > 200 m lengths
Our Approach

Why Strip Strengthened 2212 Wire?
→ Silver cannot be modified to attain required stress tolerance
   Always annealed by melt texturing even with dispersed oxide additions
   Modulus too low, ~ 80 GPa versus > 140 GPa needed if silver annealed

→ Reinforcement approach is well established for Bi2223 tape
   Which had the same silver strength problems

Why Start With Rectangular 2122/Ag?
→ Easier to reinforce than round
→ Very similar form to some commercial Nb3Sn superconducting wire
→ Better winding density in some coil configurations
→ Improved bend tolerance expected
**Wire Product Concepts**

**Rectangular Cross Section**
- Two sided form
- Reinforcement Strip
- Electrical Insulation / Reaction Barrier
- Silver Alloy Sheath
- Multifilament Region

**Round Cross Section**

**Rectangular**
- square to a 3:1

**Round**
- as needed < 1 mm to 2 mm dia.

**Strip dimension**
- selected as needed for strength and coil winding / cabling

**Stress Tolerance**
- 250 to > 400 MPa

**Je**
- > 300 A/mm² at > 20 T

**Use Modes**
- Wind & react and React & Wind
As drawn
Round wire

Deform to
Rectangular shape

Assemble with strips
On top and bottom

Diffusion Bond

Add insulation if Needed (only on edges)

Make coil from wire, or cable, then coil

Melt texture heat treat
At 1 atm or over pressure

Flexible, practical, low-cost approach for making strong 2212 wire

Alexander Otto, Solid Material Solutions, LLC: 55 Middlesex St., N. Chelmsford, MA, 978-808-9016
MEM16: 22 March, 2016
# Reinforcement Strip Selection and Key Properties

<table>
<thead>
<tr>
<th>Main criteria for candidates</th>
<th>Targets</th>
<th>Strip for early stage work</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ High modulus (ambient and 4K)</td>
<td>&gt; 200 GPa</td>
<td>~ 220 GPa (ambient)</td>
</tr>
<tr>
<td>→ High yield strain after MT (890 C) (to make use of high modulus)</td>
<td>&gt; 0.25%</td>
<td>Yield strain ~ 0.25% at ambient (~ 450 – 550 MPa yield stress)</td>
</tr>
<tr>
<td>→ BSCCO/Ag chemical compatibility</td>
<td>Good</td>
<td>Possible</td>
</tr>
<tr>
<td>→ High UTS strain for W&amp;R winding (recovered or annealed state)</td>
<td>&gt; 3%</td>
<td>&gt; 5% (annealed)</td>
</tr>
<tr>
<td>→ CTE as high as possible</td>
<td>SS or better</td>
<td>Like SS but bit &lt; CTE 2212/Ag</td>
</tr>
<tr>
<td>→ Resists oxidation in MT (890C O2)</td>
<td>Yes</td>
<td>Possible</td>
</tr>
<tr>
<td>→ Available and affordable</td>
<td>&lt; $0.5 / m</td>
<td>&lt; $0.20 / m in volume</td>
</tr>
</tbody>
</table>

This candidate looks very promising

Initially purchased strips from small mom and pop shops
Ordered much larger custom batches from quality shop – delivery 3/31
Strip Ambient Stress-Strain Pre and Post MT

Pre and post melt texture treatment stress-strain data for annealed strip used in this study and for strip with a harder wrought hard temper

Wrought temper: Pre melt texture treatment
Annealed strip: Post melt texture treatment
Annealed Strip: Pre melt texture treatment
Grip slip (Strain measured by cross-head displacement)
Modulus 210 GPa - 220 GPa

(0.8 mm x 0.1 mm)

Stress-strain properties unchanged by melt texture heat treatment
Up to 10% strain and low work hardening rate very good for wind and react
Short Straight Sample Assembly: Initial Studies

→ Prepare Surfaces
→ Stack components, to 17 cm length
→ Apply controlled compression
→ Apply bonding heat treatment
→ Evaluate properties
→ In some cases, apply 1 atm / OP MT

Good for investigating basic elements and feasibility of approach
Feasibility of Assembly, Bonding, Melt Texturing

5 to 15 cm pieces used for basic work on assembly, bonding, melt texturing (MT)

<table>
<thead>
<tr>
<th>Item</th>
<th>Width</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strips</td>
<td>0.8 mm</td>
<td>0.1 mm</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>2212/Ag</td>
<td>0.7</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

(0.8 mm dia. wire from FSU / OST)

Adhered strip with surface oxide layers

2212/Ag, no reaction seen with strips in 1 atm MT

Cut section from first test loop

0.9 mm wide SRW

Stiff, bonded, aligned, uncompromised 2212/Ag wire structures

Strips appeared very well adhered to 2212/Ag

Strips electrically insulated top and/or bottom surfaces of the 2212/Ag wire
## Development and Scale up Components

<table>
<thead>
<tr>
<th>Wire Development</th>
<th>Equipment, process, product attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coiling / Cabling</strong></td>
<td>Support development, define best mode wire use</td>
</tr>
<tr>
<td>Wind &amp; react – small coils</td>
<td>Best mode and bonded wire condition</td>
</tr>
<tr>
<td>React &amp; wind – large coils, cables</td>
<td>As above, transition from W&amp;R to R&amp;W</td>
</tr>
</tbody>
</table>

### Scale up

<table>
<thead>
<tr>
<th>Description</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>On 4 cm - 8 cm diameter mandrels: → 10 m → &gt; 50 m</td>
<td>by 5/16</td>
</tr>
<tr>
<td>On 16 cm to 25 cm diameter mandrels: → &gt; 200 m</td>
<td>by 12/16</td>
</tr>
</tbody>
</table>

### How? Expanded Collaboration as of 12/15

"Participants welcome"

- Solid Material Solutions (Core capability to make, supply bonded SRW)
- Applied Superconductivity Center / FSU (OP-MT, testing, characterization)
- Oxford Superconducting Technology (Round wire feedstock, testing)

### Funding? primarily by

- DOE Phase 2 SBIR DE-0011334, and
- The National High Magnetic Field Laboratory / Applied Superconductivity Center

---

Looking to supply wire and guidance to magnet programs

→ Prepare Surfaces

→ Co wind onto bonding mandrel

→ Apply bonding heat treatment

→ Evaluate properties

→ Use to make cable, or wind coils

→ In some cases, apply 1 atm / OP MT

Straightforward, low cost production of long lengths
Development of Mandrel Assembly, Bonding

Rectangular wire from 1.2 mm round wire, feedstock for ongoing work

Assembly on 40 mm mandrel

Bonded

Mandrel coiled samples shipped for OP and 1 atm melt texture, other studies
31 mm, 40 mm and 73 mm diameter samples
Produced ~45 coiled wires so far in 2016 for tests and development

- 40 mm and 73 mm diameter bonded 1.2 m wires
  Shipped for melt texture evaluation

- 47 mm diameter bonded wires for through process, as well as shear and bend testing

- 47 mm diameter bonded wire
  Feedstock for winding tests
Incredibly rapid turn around by FSU / ASC on first OP MT samples

<table>
<thead>
<tr>
<th>coiled SRW part</th>
<th>Area (mm²)</th>
<th>Je (4.2K, 5T) (A/mm²)</th>
<th>Ic (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip x 2</td>
<td>0.2116</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>2212/Ag inside</td>
<td>0.7791</td>
<td>530</td>
<td>425</td>
</tr>
<tr>
<td>SRW</td>
<td>0.991</td>
<td>432</td>
<td>425</td>
</tr>
</tbody>
</table>

OST supplied the round wire

SEM image
- OP MT’ d straight SRW
- 1.18 mm x 0.1 mm strips
- 1.42 mm x 0.6 mm 2212/Ag
  → Je already competitive
  → 1.07 Je direction anisotropy
  → Wider strip use on deck

73 mm mandrel
Samples For OP / Ic test
425 MPa at 0.4% strain for SRW versus 118 MPa for 2212/Ag parent
→ An ~3.5 fold improvement with 33% strip area (similar to SEI type NX)
(These data were generated at the FSU / ASC)
Bonded Strip Shear Test and Results

Loop cut from coiled bonded wire

Loop Prepared For outer strip testing

strip section abraded off

Bottom 2212/Ag wire and strip section abraded and removed

Sample for outer strip testing

Set up for outer strip bond shear test

Top strip section Abraded off

Gage length tested for shear stress tolerance

Region with 2212/Ag wire and bottom strip removed

Applied force to outer strip

Approach also tests inner strip adhesion

**Bond Shear Stress Of Recent Samples**

Outside 20 to 30 MPa exceeds need
Inside 10 to 20 MPa acceptable

Meets / exceeds estimated requirements

Note PbSn solder also 25-30 MPa
Bonded Wire Bend Test

Test Method
- 5 cm test pieces
- Manual wrap
- Release
- Examine for delamination
- Trace inner curve
- Measure chord span n height
- Calculate rebound diameter
- Photograph sample
- Bend to next smaller diameter

Factors
- Bend limit to delamination
- Rebound diameter
- Strip bend and rebound strain
- Bending force / tension
- Internal bend-induced pressure

Traced inner curves
For estimating rebound radius

Example of rebound

Tested double sided and single sided wire samples

Bonded Wire Bend Progression

**Double / single sided:** Strips on both / one side

**Bonded SRW can take extreme bending w/o delamination**

Very good news for cabling and coiling

Bonded Wire Bend and Rebound Strain Results

Average Axial Strain In Strips for Forward and Reverse Bending From As-Bonded Diameter

- 2212/Ag Strip: 0.6 mm x 1.4 mm
- Bonded Diameter: 73 mm
- Bend Orientation: Through thickness

Wires undamaged even in reverse 9.5 mm diameter bends

Bonded Strips Support > 4% Axial Strain Without Delaminating or Breaking (In Reverse and Forward Bend Directions)
Solenoid Concepts With SRW

**SRW solenoid features, wind and react**
- No insulation may be needed (in most cases)
- Radial epoxy penetration to fill gaps
- Good stress sharing, space filling
- Easy to grade amount of reinforcement
- Can use *single* and *two sided wire types*

**Single sided SRW**
- Bonding in MT greatly strengthens structure

**Two sided SRW**
- Not bonded in MT

---

**High wind density, variety of possible architectures and forms**
High Current Transposed Cable Concept

Example: Cable comprised of two sided SRW
- No insulation needed
- Planetary lay up
- Short pitch length (~ 8 - 15 X cable width)
- Fully transposed
- Flexibility in architecture
- In conduit of needed
- Wind and React and React and Wind regimes

Design: Bend and stress tolerance from test data

<table>
<thead>
<tr>
<th>Max Field (4K)</th>
<th>20 T</th>
<th>30 T</th>
<th>40 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Current (0.8 x Ic)</td>
<td># Wires</td>
<td>Cable Width</td>
<td># Wires</td>
</tr>
<tr>
<td>5 kA</td>
<td>15</td>
<td>11 mm</td>
<td>18</td>
</tr>
<tr>
<td>10 kA</td>
<td>30</td>
<td>22 mm</td>
<td>38</td>
</tr>
</tbody>
</table>

Rectangular 2212/Ag wire: 1.4 mm x 0.7 mm, with Je of 600 A/mm² at 4K, 5T
Wire Testing for Coiling and Cabling

Straightening and unwinding current mandrel-bonded wire

73 mm diameter bonded wire readily straightened by reverse direction take up wind, with no delamination

200 mm Dia.
73 mm Dia.

Front end of coiled wire
Straightened by rewind

Alexander Otto, Solid Material Solutions, LLC: 55 Middlesex St., N. Chelmsford, MA, 978-808-9016
MEM16: 22 March, 2016
First Bonded Wire Coiling Tests

- 2-layer mini coils with as-bonded wires
  - 16 to 20 turns
  - 1.25 to 2 cm diameter
- Single sided reinforcement
  - Re-do bonding heat treat
  - Very well bonded and rigid coil obtained
- Double sided reinforcement

  - 2 cm diameter coil
    - Double sided SRW
    - 1.4 mm x 0.6 mm 2212/Ag
    - 1.18 mm x 0.11 mm strips (2)

  - 1.4 cm diameter coil
    - Single sided SRW
    - 0.85 x 0.4 mm 2212/Ag
    - 1 x 0.05 mm strip (1)

Alexander Otto, Solid Material Solutions, LLC: 55 Middlesex St., N. Chelmsford, MA, 978-808-9016
MEM16: 22 March, 2016
First Cabling Test: No problems with 5 cm pitch

**Goal**

Basis for, and feasibility of making transposed cables with 2212 SRW

<table>
<thead>
<tr>
<th>Wire Used</th>
<th>C9</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRW</td>
<td>1.42 mm</td>
</tr>
<tr>
<td>2212/Ag</td>
<td>1.42 mm</td>
</tr>
<tr>
<td>Strips</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Assembly</td>
<td>73 mm mandrel</td>
</tr>
<tr>
<td>Bonding</td>
<td>Early process</td>
</tr>
</tbody>
</table>

**Cable**

| Number of wires | 5          |
| Straightening   | 20 cm reverse wind |
| Wire shaping    | Before cabling |
| Former radii    | 5 cm edge, 3.2 cm flat |
| Pitch           | 50 mm      |
| Assembly        | Manual     |
| Damage observed | None       |
| Type            | Loose fit  |
| Max wire edge strain | 2.5% (to >5% is ok) |
| Assessment      | No delamination |

**Excellent result, cabling test validated bend test data**

Strip slightly wider than 2212/Ag likely to be better – await custom strip delivery

Alexander Otto, Solid Material Solutions, LLC: 55 Middlesex St., N. Chelmsford, MA, 978-808-9016

MEM16: 22 March, 2016
Summary

Proof of concept demonstrated for strong 2212 wire

1) 2212 wire with > 400 MPa stress tolerance at 0.4 % strain
2) Je of SRW exceeds 400 A/mm2 (5T 4K)

Approach scaled up to a first generation pilot mandrel process

1) Produced 45 bonded wire samples in development, 31 – 73 mm dia.
2) Attain 25 – 30 MPa shear strength of strips bonded to 2212/Ag – like solder
3) As-bonded SRW wire can be bent to < 1 cm diameter w/o damage
4) Scaling up to make > 50 m piece lengths by 5/16, > 200 m lengths by 12/15
5) Prepared to produce and supply SRW, bonded or fully reacted (SMS-1atm)
THANK YOU