Advances in Overpressure Processing Bi-2212 Insert Coils in a New, Large Overpressure Furnace


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Overview

• What is overpressure (OP) processing and why do we need it?
• Research-scale OP studies
• Large-scale OP studies
Drawbacks of 2212
- 2212 can only be used up to 10 – 15 K
- Much higher $J_c$ in 2212 flat tape
- 2223 and REBCO are better HTS flat tapes and can be used at 77 K

1989 – first Bi-2212 round wire
Why the renewed interest in Bi-2212?

High-field critical current densities in $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+x}$/Ag wires

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Why Bi-2212 now?

- Round wire has versatile application potentials for high-field NMR magnets and accelerator magnets etc.

- Multifilamentary and does not have macroscopic electromagnetic anisotropy.

- Twisted wire with significant reduction of hysteretic losses.

- A high irreversibility field - above 100 T at 4.2 K.

- Overpressure (OP) processing makes $J_E$ of Bi-2212 very competitive.

Round wire is preferred conductor geometry to build magnets

1.1 T in 31 T - first HTS wire-wound coil to go beyond 30 T

Cables for very-high-current applications

Myers, Trociewitz

10 cm

Rutherford

Godeke

Shen

6-on-1
2212 powder in 2212 wire is ~60% dense - bubbles form in 2212 RW during heat treatment

Before

Ag(Mg) Sheath

2212 powder (black)

Pure Ag between filaments (white)

200 μm

OST

After

Bubbles

X-ray tomography
Scheuerlein, Di Michiel, Scheel
Removing bubbles with overpressure (OP) processing more than doubles $J_E$

Direct observation of gas-filled bubbles due to powder being only 60-70% dense

OP processing squeezes wire with gas pressure to remove bubbles

$J_E = 725 \text{ A/mm}^2 @ 20 \text{ T}$

Closed-end wire @ 1 bar OP

~2.5x

~6-7x

Closed-end wire @ 1 bar OP = long coil

Kametani, Jiang, Matras, Craig
Overpressure processing is a form of Hot Isostatic Pressing (HIP)

OP processing – gas pressure squeezes wire to remove bubbles
• Flow-through mixture of Ar and O₂
• Total OP pressure ≤ 100 bar
• Wire or tape must be hermetically sealed
  • Ag sheath provides the seal

• Ar – presses on Ag sheath – removes bubbles
• O₂ – diffuses through Ag - sets thermodynamic condition needed to form Bi-2212
• Use an Ar/O₂ gas mixture that sets pO₂ = 1 bar in the OP system
OP processing improves $J_c$ by two mechanisms

- Compresses wire so volume of Bi-2212 matches filament cavity
  - Removes bubbles

- Prevents gas from expanding
  - $\text{CO}_2$, $\text{H}_2\text{O}$
  - Eliminates dedensification and creep-induced leakage
What can happen to 2212 filaments during melt processing?

- Maximum packing density of 2212 powder in filaments is 60-70%
- Focus on the 30-40 vol% of the filament that is gas-filled void space

60% dense 2212 powder in as-drawn wire
Best case with 1 bar processing:
30-40 vol% gas bubbles in filament

1 bar – clean powder, no CO₂, H₂O

60% dense

40 vol% gas

60 vol% melt

Kametani

Scheuerlein

- Video shows filaments in 2212 wire during heating and cooling in 1 bar air.
Worst case with 1 bar processing: dedensification and leakage

Internal gas pressure expands filament hole

1 bar – dirty powder: CO$_2$, H$_2$O

60% dense

• Malagoli
• Shen

Scheuerlein
Best processing: apply overpressure to squeeze Ag so filament hole matches 2212 volume $\Rightarrow$ 100% dense

External overpressure decreases filament hole

100 bar – dirty or clean powder

60% dense

100% vol% melt

OP decreases wire diameter

Scheuerlein
60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:

60% dense

25 vol% melt

75 vol% gas

60 vol% melt

40 vol% gas

1 bar

–

dirty powder: CO$_2$, H$_2$O

60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:

60% dense

25 vol% melt

75 vol% gas

60 vol% melt

40 vol% gas

1 bar

–

dirty powder: CO$_2$, H$_2$O

60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:

60% dense

25 vol% melt

75 vol% gas

60 vol% melt

40 vol% gas

1 bar

–

dirty powder: CO$_2$, H$_2$O

60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:

60% dense

25 vol% melt

75 vol% gas

60 vol% melt

40 vol% gas

1 bar

–

dirty powder: CO$_2$, H$_2$O

60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:

60% dense

25 vol% melt

75 vol% gas

60 vol% melt

40 vol% gas

1 bar

–

dirty powder: CO$_2$, H$_2$O

60% dense

100 vol% melt

40 vol% gas

1 bar – dirty powder: CO$_2$, H$_2$O

1 bar – clean powder:
Demonstrated that OP processing works for Bi-2212 with small-bore OP system

- Small OP system originally designed, built, and used for Bi-2223

ASC’s 2.5-cm bore research OP system

Sumitomo Electric’s 4-story-tall OP system for commercial Bi-2223 tape
Overpressure (OP) densifies 2212 wires

Closed ends 1 atm: gas trapped <60% dense

Overpressure (OP) densifies 2212 wires

Closed ends 1 atm: gas trapped <60% dense

Closed ends 100 atm OP:
0.8 mm diameter
closed ends 8 cm long samples

Assumption: closed ends short samples behave the same as long coil length

1 atm closed ends
expansion

As-drawn 60% dense

Densification

100 atm closed ends
Dense filaments are the key for high $J_E$

- $J_C$ is calculated using the as-drawn wire filament cross sectional area (60% dense filaments)
- $J_C$ increases (actually it triples) with decreasing wire diameter as full physical connectivity occurs.

\[ J_E = \frac{I_C}{\text{area OP wire}} \]

\[ J_C = \frac{I_C}{\text{area filament as – drawn wire}} \]

Experiment done on short wires (8 cm long)

Matras
OPed 2212 coil at 10 bar - generated 2.6 T in 31.2 T background = 33.8 T

10 bar OP processing
• Pressure was only high enough to prevent wire from expanding
• Did not compress Ag sheath and remove bubbles
• Insulation - ~15 μm thick TiO₂
Deltech built a large OP furnace for Bi-2212 coils - custom built, first of its kind

ASC’s 2.5-cm bore research OP system

Deltech 100 bar OP furnace
50 bar processing is adequate for NMR demonstration coil

Experiment done on short wires (8 cm long) (37x18)

- 35 m long 10 bar coil fell on the curve
After 100 bar 821°C-12h

100 bar OP significantly decreases the wire diameter.

**Issue:**
For magnet construction, this change in diameter poses an interesting challenge.

**4.2 % decrease in wire diameter at 100 atm**

![Graph showing decrease in wire diameter](image)
OP furnace and coil being developed together for high-field NMR project

High field coil + shim coils for 1 GHz (24 T) NMR demonstration magnet

Mockup of coil for NMR demonstration project

- 6.6 T
- 240 mm high
- 92 mm OD
- 44 mm ID
- 0.7 km wire
- 179 turns
- 18 layers

Platypus team
“Platypus”: A Bi-2212 NMR Demo-Magnet

Goals:
• **MagSci Goal:** 30 T NMR magnet using HTS
• NMR demo magnet of ~1 GHz (24 T) with ppm field homogeneity and stability
• Hybrid LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb$_3$Sn + 8 T Bi-2212)

Status:
• Novel 2212 HTS technology has been led by NHMFL
• All sub-systems demonstrated
• Platypus test planned for summer 2015
• Strong DOE-HEP and CERN support for conductor development with industrial partner OST

Bismuth Strand and Cable Collaboration  BSCCo
Long-length insulation developed in-house – now SBIR partner with nGimat

Coating system

Insulation coat

• TiO$_2$ particles suspended in organic binder
• $\sim 30 \, \mu$m thick adherent coating
• Burn out before OP heat treatment

In-house coated test-coil
Platypus test coils 2015 ("Platypups")

- Test coils demonstrated:
  - Thermally homogeneous processing of long, thick coils
  - Reasonable correlation of coil and finite element analysis models
  - Viable terminal design
  - 4% wire densification being dealt with
  - Successful epoxy impregnation
- Some coils have been tested in 17 T background at the NHMFL
- Some coils have been dissected for further analysis of the winding pack and transport characterization of extracted coil segments
- Two additional Platypup test coils done in June 2015

Platypus team
Platypus test coils

• Platypus test coils
  • Platylong – full length, 3 layer
    Evaluate sag from 4% wire shrinkage, furnace uniformity
  • Platypup 1 – 1/10 length, full thickness
    Impregnation, leads, insulation, 17 T test

• Platypup 2 – 2/10 length, full thickness (smaller diameter wire)
  Impregnation, overbanding, confirm FEA modelling, 17 T test

• Platypup 3 – 1/10 length, full thickness
  Impregnation, variations in coil winding, 17 T test
The pluses and minuses of 2212

Pluses

- Round, multifilament and twisted
  - Small magnetization and small field errors
  - Highest $J_E$ of any present HTS
  - Isotropic electromagnetic properties
- Flexible architecture
  - Not one-size-fits-all, like REBCO and Bi-2223

Minuses

- Must be wound in unreacted form and taken through complex HT by magnet builder under 20-100 bar pressure (1 bar $O_2$) at up to 890 °C
- Must be insulated prior to heat treatment – done!
- 4% densification under pressure needs compensation – being addressed!
- Wire is mechanically weak
Summary

- OP processing makes Bi-2212 round wire a viable conductor for high-field magnets – single strand or cables
- Round wire geometry – or wire with small aspect ratio – is preferred geometry to build magnets
- Bi-2212 being used in 1 GHz (24 T all SC) demonstration NMR magnet
- Subscale coils are being tested on path to full-scale NMR demonstration coils