A-15 Inhomogeneity

The Underestimated Enemy of High-Performance Nb$_3$Sn Wires

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April 10, 2018 — FCC Week
Introduction

The Problem

Examinations

Radial Inhomogeneity

EDX results

SHPM results

Local Variations

Different ‘magnetic look’ of sub-elements

Critical temperature

Intra-granular Sn concentration gradients

Simulations

Pinning force scaling

High-field performance

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5. Conclusions
 Nb$_3$Sn is formed during heat treatment by diffusion reaction
Introduction
The Problem

- Nb$_3$Sn is formed during heat treatment by diffusion reaction
- In modern wires a Sn source diffuses outwards into a region containing densely stacked Nb filaments (RRP) or a Nb tube (PIT)
Introduction

The Problem

- Nb$_3$Sn is formed during heat treatment by diffusion reaction
- In modern wires a Sn source diffuses outwards into a region containing densely stacked Nb filaments (RRP) or a Nb tube (PIT)
- Consequently, a radial gradient in stoichiometry is always present
- Other types of inhomogeneities, such as sub-element sausaging or barrier breakage, may also occur
Introduction

Examinations

- **Energy-dispersive X-Ray (EDX) analysis**
  Change of chemical element concentrations within sub-element cross sections

- **Scanning Hall Probe Microscopy (SHPM)**
  Magnetization maps of individual sub-elements, $T_c$ distribution within sub-elements, and variation between sub-elements

- **SQUID magnetometry**
  $T_c$ obtained from AC susceptibility measurements
**Simulations**
Effects of radial Sn concentration gradients on pinning force scaling behavior and high-field performance

- Sub-element is sub-divided into many current carrying elements
- Sn concentration of these elements varies with radial position
- $T_c$ and $B_{c2}$ are computed based on Sn content\(^1\)
- $J_c(T, B)$ is computed from intrinsic properties and grain size\(^2\)

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\(^1\) Y. Li, Y. Gao: *Sci. Rep.* 7, 1133, 2017
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Radial Inhomogeneity

EDX results

- Linear decrease of Sn concentration over wide radial range, and a steep fall-off near the barrier
- Similar behavior found in RRP and PIT wires
- Typical gradient in linear region: $\sim 0.1 \text{ at.}\%/\mu\text{m}$
Radial Inhomogeneity

SHPM results

\[ T = 11 \text{ K} \]

- SHPM was done on wire cross sections in the Meißner phase
- Wire sample is cooled, then a small field of (typically 5 mT) is applied
- Scanning at different temperatures allows visualizing the penetration of the magnetic field and hence the radial \( T_c \) gradient\(^3\)

\(^3\)T. Baumgartner et al.: *Supercond. Sci. Technol.* 30, 014011, 2017
Radial Inhomogeneity

SHPM results

\( T = 15 \text{ K} \)

- SHPM was done on wire cross sections in the Meißner phase
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Local Variations

Different ‘magnetic look’ of sub-elements

- SHPM on 1 mm long sample in remanent state shows large variations in size and shape of sub-elements as well as in remanent field (and consequently $J_c$).
- This was not expected based on SEM images of the cross section.
- Indication of longitudinal variation of superconducting properties?

![Image of magnetic field distribution with 50 μm scale]

$B$ (T)

0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28 0.32
Local Variations
Different ‘magnetic look’ of sub-elements

- SHPM on 1 mm long sample in remanent state shows large variations in size and shape of sub-elements as well as in remanent field (and consequently $J_c$)
- This was not expected based on SEM images of the cross section
- Indication of longitudinal variation of superconducting properties?
AC susceptibility measurements revealed large differences between \( \sim 10 \mu m \) thick disk cut from the wire and 4 mm long sample. \( T_c \) onset appears to be identical, but transition is much broader in thin sample.
SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample.

At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside.

\[ T = 13 \text{ K} \]
Local Variations

Critical temperature

\[ T = 14 \text{ K} \]

- SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample
- At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside
Local Variations
Critical temperature

\[ T = 15 \text{ K} \]

- SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample.
- At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside.
Local Variations

Critical temperature

- Local $T_c$ measurements on a 1 mm thick sample
- Sample magnetized, Hall probe positioned over one sub-element, temperature slowly ramped up
- Deviations indicate different $T_c$ distributions
Local Variations

Intra-granular Sn concentration gradients

- Large Sn concentration gradients found inside individual grains by TEM-EDX
- Impact on $J_c$ not yet clear, but adverse effect due to suppression of superfluid density is possible
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Simulations
Pinning force scaling

- $F_p = |\vec{J}_c \times \vec{B}|$ at different temperatures is mapped onto single curve by normalizing $F_p$ to maximum value and $B$ to scaling field $B_{c2}^*(T)$
- $f(b) = C b^p (1 - b)^q$
  Unified Scaling Law pinning function\(^4\)
- Shape determined by two exponents which depend on the pinning mechanism\(^5\)
- $p = 0.5, \; q = 2$ for Nb\(_3\)Sn (grain boundary pinning)

\(^5\) D. Dew-Hughes: *Phil. Mag.* 30, 293–305, 1974
Simulations

Pinning force scaling

Inhomogeneities lead to deviations from scaling behavior, since the material does not have a single $T_c$ and $B_{c2}$.

Scaling analysis results depend on accessible temperature and field range (here 4.2–15 K, 0–7 T).

Bad extrapolations of $J_c$ to higher field values can be the result.$^2$

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Simulations
High-field performance

- Realistic Sn concentration profile used as input for simulation software
Simulations

High-field performance

- Realistic Sn concentration profile used as input for simulation software
- Two hypothetical profiles with improved homogeneity simulated for comparison
Simulations
High-field performance

$J_c(B)$ at 4.2 K obtained from simulations

$J_c(10^9 \text{A} \cdot \text{m}^{-2})$ vs. $B$ (T)

- $J_c(B)$ at 4.2 K obtained from simulations
- Critical temperature
- Intra-granular Sn concentration gradients
- Different ‘magnetic look’ of sub-elements
- Simulations
- Pinning force scaling
> $J_c(B)$ at 4.2 K obtained from simulations
> Significant increase possible by reducing the radial inhomogeneity
Simulations
High-field performance

- $J_c(B)$ at 4.2 K obtained from simulations
- Significant increase possible by reducing the radial inhomogeneity

![Graph showing $J_c(B)$ vs. $B$ for different gradients.]

- no gradient
- gradient reduced by 50%
- realistic

$J_c(10^9 \text{ A}\cdot\text{m}^{-2})$ vs. $B$ (T)
Radial Sn concentration gradients inside sub-elements cause a significant spatial variation of the superconducting parameters.

$T_c$ gradients inside individual sub-elements can be examined using SHPM.

Evidence for longitudinal inhomogeneities was also found.

Variation of Sn content within individual grains was found, but importance is not yet clear.

Inhomogeneities cause deviations from scaling behavior, which can lead to incorrect $J_c$ extrapolations to higher field values.

Performance can be improved significantly by reducing radial Sn gradients.

*Poster recommendation: 2AMSP45 (S. Pfeiffer on TEM examinations of Nb$_3$Sn wires)*
Thank you.

I am just a child who has never grown up.
I still keep asking these ‘how’ and ‘why’ questions.
Occasionally, I find an answer.
— Stephen Hawking