Status and perspective of the Nb$_3$Al development in Japan

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Advantages of RHQT Nb$_3$Al over Nb$_3$Sn

better strain tolerance
higher $B_{c2}(4.2K)$: 30 T

Large scale application
Fusion, Accelerator

by Ekin
Advantages of RHQT Nb$_3$Al over HTS

- Easy superconducting joint
- Large $n$-value
- Tolerance to stress and strain

Application

- High-field NMR spectroscopy
Specification of $\text{Nb}_3\text{Al}$ conductor for NMR uses

- Rectangular
- Stabilizer (Cu clad)
- Nb matrix (superconducting)
- DC (filament diameter, spacing)
- Optimization of $J_c$ (4.2K) at 21 T
Advanced A15 Compounds

- Nb₃Al
- Nb₃Ga
- Nb₃(Al,Ge)

Off-stoichiometry at LT

New approach

RHQT technique
(rapid-heating, quenching and transformation)
stoichiometry without grain growth

Manufacture: binary reaction, Al dimension: < 100nm

Diffusion process (750°C x 50h)
11-14 T, off-stoichiometry
Cu-matrix JR

RHQT process (1900°C + 800°C x 10h)
12-23 T, stacking faults
Nb-matrix JR

New process (TRUQ, DRHQ)
21-25 T
Joule Heating

Quenching

Precursor:

Nb/JR

Al sheet

Nb/Al sheet

Nb rod

Winding

Transformation

Cu/Nb/Nb(Al)ss

Extrusion + Drawing

Precursor: Nb/JR

Joule Heating + Quenching

Nb/Nb(Al)ss

Cu cladding

Winding + Transformation

Cu/Nb/Nb(Al)ss

Cu/Nb/Nb3Al

Vacuum

Gallium bath

Power supply

Ohmic heating

Infrared radiation thermometer

Take-up spool

Payoff spool

Copper wheel

Vacuum

Jelly-roll

Al sheet

Nb rod

Nb sheet
Long-length of RHQ processing

- Plateau region (150°C): optimum
- Insensitivity to unwanted temperature scatter
- Uniformity of SC properties along a long-length of wire
Distributions of $T_c$ and $J_c$ along a 300 m length of wire

- Constant current power supply

\begin{itemize}
  \item Wire diam.: 1.35 mmφ
  \item Nb/Nb$_3$Al ratio: 0.81
  \item Fil. No.: 132
  \item Fil. diam.: 89 µm
\end{itemize}

(a) Current variation

(b) Voltage variation

\begin{itemize}
  \item Critical Temperature (K)
  \item Critical Current (A)
  \item Position along a 300 m length of conductor (m)
\end{itemize}

Standard deviation of $J_c$ (4.2K&21T) : 5 %
Deformability of Nb(Al)ss at RT

Tensile test at room temperature

Sample #1 (1.275mmφ, 0% RA)
Temperature: 20°C
Strain Rate: 6.25 x 10^-4 sec^-1

Incorporation of Cu stabilizer by mechanical cladding
Jc improvement

Ic vs. Reduction in Area, R.A. (%)

Cu-cladding JR Nb 3Al
Temperature ramp-up rate at transformation annealing

Deformation

$J_c$ enhancement
Less sensitive to ramp rate
# Coil specifications

## TABLE I

### SPECIFICATIONS OF WIND & REACT Nb$_3$Al SOLENOID COILS

<table>
<thead>
<tr>
<th></th>
<th>Previous</th>
<th>Present</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M11-1</td>
<td>ME332</td>
<td>ME356</td>
</tr>
<tr>
<td>RHQT JR Nb$_3$Al conductor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilizer</td>
<td>Cu-clad</td>
<td>Cu-clad</td>
<td>Cu-clad</td>
</tr>
<tr>
<td>Piece length (m)</td>
<td>35</td>
<td>370</td>
<td>370</td>
</tr>
<tr>
<td>Cross section (mm$^2$)</td>
<td>1.61x0.71</td>
<td>1.82x0.84</td>
<td>1.81x0.80</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>70</td>
<td>74</td>
<td>75.5</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>84</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Cu/non-Cu ratio</td>
<td>0.45</td>
<td>0.38</td>
<td>0.39</td>
</tr>
<tr>
<td>Insulator</td>
<td>Al$_2$O$_3$ fiber</td>
<td>Al$_2$O$_3$ fiber</td>
<td>Al$_2$O$_3$ fiber</td>
</tr>
<tr>
<td>Winding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner diameter (mm)</td>
<td>19.7</td>
<td>90.2</td>
<td>64.6</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>40.8</td>
<td>111.8</td>
<td>99.3</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>49.7</td>
<td>200</td>
<td>132.4</td>
</tr>
<tr>
<td>Number of turns</td>
<td>311</td>
<td>949</td>
<td>988</td>
</tr>
<tr>
<td>Total length of wire</td>
<td>30</td>
<td>300.5</td>
<td>254</td>
</tr>
<tr>
<td>Coils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impregnation</td>
<td>Beeswax</td>
<td>Beeswax</td>
<td>Beeswax</td>
</tr>
<tr>
<td>Transformation</td>
<td>RT$\rightarrow$(5h)$\rightarrow$800$^\circ$C$\rightarrow$(10h)$\rightarrow$800$^\circ$C$\rightarrow$RT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil constant (T/A)</td>
<td>0.00106</td>
<td>0.00562</td>
<td>0.00797</td>
</tr>
</tbody>
</table>
**n-value** \((10^{-5} - 10^{-4} \text{ V/m})\)

Consistency of \(I_c\)
point, tail of 370 m

\(n\)-value
25@21T, 4.2K

\[ V = \text{Const.} \, I^n \]

voltage taps spacing: 25 cm
fitting range: 2.5\(\mu\)V-25\(\mu\)V

370 m length of Cu-clad conductor

0.1 \(\mu\)V/cm criterion

4.2 K
\( I_q \) (coil) > 0.9 \( I_c \) (short samples)

Uniformity of a long-length of RHQ operation over 300 m

・RHQT Nb_3Al is really reliable for practical coil application.
- 1 kA I_c probe
- Measurement of J_c of round wire electroplated with Cu in fields from 8 to 17 T
- Optimization
  - wire diameter: 0.8 → 0.69 mm
  - RA: 20% (< 40% for 21T)
  - transformation HT: 775°C15h
- Highest J_c: 1730 A/mm² at 10 T

Sample length: 300 mm
Large cross section of Cu: 72 mm²
Heating at 1000 A: < 80 mW/lead
(ΔT < 10 mK)
Internal Stabilization

1. Less expensive
2. Round cross section of wire
3. Possible high current conductors (CICC, Rutherford cables, etc)
4. No contamination of Ag with Ga
5. Large RRR (200)
6. Applicability to high temperature transformation (TRUQ, DRHQ)
Trial Manufacture of High-Current RHQT Nb₃Al Conductors

Critical Current, $I_c$ (A)

Magnetic Field, $B$ (T)

$I_c$ at 14 T
Measure: 3.49 kA
Design ($I_c$, strand x 16): 3.7 – 4.3 kA

7% degradation

Cable-in-Conduit Conductor for Fusion Uses

The 1st triplet: a Nb₃Al, two Cu

The third stage cable: 3 x 4 x 4

Internally stabilized Nb₃Al strand

0.8 mm Φ
Ag/non-Ag:0.17
Measurement_1

V taps spacing: 100 mm, 375 mm
Current ramp rate: 30A/sec, 60A/sec
**Table 1** Specifications of measured JR Nb$_3$Al wires.

<table>
<thead>
<tr>
<th>Sample</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of wire (mm)</td>
<td>0.507</td>
<td>0.89</td>
<td>1.275</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>36</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>Diameter of filament (µm)</td>
<td>55</td>
<td>76</td>
<td>108</td>
</tr>
<tr>
<td>Average thickness between filaments (µm)</td>
<td>2.8</td>
<td>6</td>
<td>9.4</td>
</tr>
<tr>
<td>Nb/Non-Nb ratio</td>
<td>1.5</td>
<td>1.39</td>
<td>0.59</td>
</tr>
</tbody>
</table>

**Matrix: Nb**

Flux jump

Not desirable for fusion and accelerator magnets

**AC Loss**

- bridging
- proximity effect
Manufacture of Ta matrix JR Nb₃Al wire by Tatsumi et al

Ta core-Ta barrier

Ta tube (sheath)
Ta dummy

Ta barrier
Ta core
Nb/Al Jerry-roll

2 other filament structures

Ta core-Nb barrier
Nb core-Nb barrier (conventional)
# Workability

<table>
<thead>
<tr>
<th>Wire Diameter</th>
<th>No of filaments</th>
<th>Filament diameter</th>
<th>Matrix ratio (non JR / JR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ 0.8mm</td>
<td>66</td>
<td>φ 65 μm</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structure</th>
<th>Cross section</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta core-Ta barrier (フィラメント間:Ta JRコア:Ta)</td>
<td>![Cross section image]</td>
<td>Very Good (no breakage until φ 0.5mm)</td>
</tr>
<tr>
<td>Ta core-Nb barrier (フィラメント間:Nb JRコア:Ta)</td>
<td>![Cross section image]</td>
<td>Good (no breakage)</td>
</tr>
<tr>
<td>Nb core-Nb barrier (フィラメント間:Nb JRコア:Nb)</td>
<td>![Cross section image]</td>
<td>Good (no breakage)</td>
</tr>
</tbody>
</table>
Magnetization curve

Ta matrix

- suppression of flux jump

Other advantages
- high strength at high temperature
- no formation of Ga-rich compound on a surface
- less induced-radioactivity
Potential of RHQT Nb₃Al

![Graph showing the relationship between non-Cu Jc (A/mm²) and B (T) for different materials including RHQT Nb₃Al, TRUQ Nb₃Al, DRHQ Nb₃Al, RRP Nb₃Sn (OST), 16% Sn Bronze Nb₃Sn, and 14% Sn Bronze Nb₃Sn. The graph highlights the performance of RHQT Nb₃Al at 4.2 K.](image)
A15-type Nb₃Al

BCC Nb(Al)ss

10 sec~10 min transformation

Heat

Temperature (°C)

Time

TRUQ: time for 1 to 3 steps < 0.3 sec

1. Ignition (nucleation of transformation)
2. Thermal explosion
   - Propagation of the transformation interface
   - Transform to A15 via highly disordered bcc phase
     low long-range order
     free from stacking faults
3. Self-turn down to ambient temperature
4. Annealing for long-range order

Similar to a combustion synthesis
Microstructure

Distance between Adjacent Stacking Faults

Ave. 8.8 nm

Ave. 19.7 nm

Subgrain Diameter (nm)

Ave. 52 nm

By N. Banno et al.
Microchemical homogeneity in filaments
↓
Sharp transition
↓
Enhancement in Jc

Non-uniformity

TRUQ $\chi'$
TRUQ $\chi''$
700C-10h/800C-10h $\chi'$
700C-10h/800C-10h $\chi''$
800C-10h $\chi'$
800C-10h $\chi''$
Optimization for Jc

under the condition of ordinary transformation that enables W&R coil (~800°C, ramp rate of 1-5 h/800°C)

**Parameters**

- Wire diameter
- Nb matrix ratio
- No. of JR filaments
- Filament diameter
- Inter-filament spacing
- Nb/Al ratio
- layer thickness
- Alloying
- Joule heating current density
- Heating distance
- Wire speed at RHQ
- R.A. after RHQ
- Transformation HT

**Microchemistry**
- Crystal imperfection
  - bcc grain, ordering
  - A15 grain
  - Stacking faults
Ongoing improvement of JR Nb₃Al

![Graph showing non-Cu J_c vs. B (T) for different materials: RHQT Nb₃Al, TRUQ Nb₃Al, DRHQ Nb₃Al, RRP Nb₃Sn (OST), 16% Sn Bronze Nb₃Sn (Kobe), 14% Sn Bronze Nb₃Sn, and optimization ongoing RHQT Nb₃Al. The graph indicates improvements in J_c at 4.2 K.]
Development Schedule

• Long-length of precursor (>2km) large billet
• Long-length of RHQ processing (>2km) large-scale RHQ apparatus: under construction
• Reel-to-reel Cu ion plating installation, trial operation

Target: piece length of more than 2 km for 1.35 mmφ wire
Multifilament billet (50kg)

No breaking during drawing of wire

Piece-length: 2.6 km for Φ 1.35 mm wire

(corresponding to 9.7 km for Φ 0.7 mm wire)
Prototype RHQ-apparatus

- >2 km length of 1.35mm Φ precursor-wire
Prototype reel-to-reel ion plating apparatus
Reel-to-reel Cu ion plating apparatus_2
Summary

• Large multifilament billet: 52 kg
• Piece length of precursor (1.35 mm): 2.6 km
• RHQ apparatus: just installed
  300 m → ? km
• Non-Cu Jc improvement (21T): Ongoing
• Stabilization of a round wire
  internal stabilization
  Cu ion plating and electroplating