Development progress in KAT

10th Apr. 2018
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Outline

- Introduction
- Development progress of Nb₃Sn strand for FCC
- Plan for performance improvement
- Conclusion
Collaboration agreement between CERN and KAT was established in Mar-2017.
Kick-off meeting was conducted in 21 Mar-2017.
The purpose of this program is to achieve Jc target.
Introduction

- Local collaboration for Nb₃Sn development

- Hydrostatic extrusion process
- Wire design consultation
- Low temperature test at 16T, 4.2K
- Strand performance test

Strand design and manufacture
Project management
### Design summary for FCC target

- **Stabilizer Cu**
- **Ta barrier**

#### Type I

- Cu/Nb_199
- Mono Cu/Nb
- Cu/SnTi

#### Type II

- Cu/Nb_multi/SnTi
- Cu/SnTi

#### Type III

- Cu/Nb_multi/SnTi
- Cu/SnTi

### Designed parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Type I</th>
<th>Type II,III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cu/N-Cu</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>No. Filaments</td>
<td>ea</td>
<td>11,940</td>
<td>48,678</td>
</tr>
<tr>
<td>Dia. Filament</td>
<td>μm</td>
<td>4.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Dia. Sub't</td>
<td>μm</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>Cu fraction</td>
<td>%</td>
<td>15.7</td>
<td>14.8</td>
</tr>
</tbody>
</table>

### Estimation of performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Type I</th>
<th>Type II,III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono Ic</td>
<td>A</td>
<td>0.036</td>
<td>0.0127</td>
</tr>
<tr>
<td>Ic</td>
<td>A</td>
<td>430</td>
<td>618</td>
</tr>
<tr>
<td>Jc</td>
<td>A/mm²</td>
<td>1,100</td>
<td>1,574</td>
</tr>
</tbody>
</table>
Development progress

Manufacturing process of Type I

- Cu/Nb mono-rod
  - H. Extrusion + Cold drawing

- Cu/Nb multi-rod(199M)
  - H. Extrusion + Cold drawing

- Restacking billet
  - Cold drawing

Manufacturing process for Type I strands

[Advantage]
- Relatively simple process
- Low manufacturing cost

[Disadvantage]
- Non-uniform diffusion of Sn and Ti
- Optimization of heat treatment
Development progress

Manufacturing process of Type II and III

Cu/Nb mono-rod
H. Extrusion + Cold drawing
Size cutting + Assembly

Cu/Nb multi-rod (19M)
H. Extrusion + Cold drawing
Size cutting + Assembly

[Advantage]
- Uniform performance
- Easy to optimize HT
- Smaller Nb filaments

[Disadvantage]
- Complicate process
- High Cu fraction in matrix
- Wire breakage

Manufacturing process of Type II & III

Sub element
Cold drawing
Restacking billet
Cold drawing

[Advantage]
- Uniform performance
- Easy to optimize HT
- Smaller Nb filaments

[Disadvantage]
- Complicate process
- High Cu fraction in matrix
- Wire breakage
Development progress

Manufacturing results of Type I samples

<table>
<thead>
<tr>
<th>Design</th>
<th>Diameter [mm]</th>
<th>Cu/Non-Cu</th>
<th>Nb/Sn</th>
<th>$A_{mat\text{,Cu}}$</th>
<th>No. Nb module</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>0.92</td>
<td>1.38</td>
<td>15.3%</td>
<td>56 EA</td>
</tr>
<tr>
<td>2</td>
<td>1.00, 0.816, 0.7</td>
<td>0.93</td>
<td>1.89</td>
<td>15%</td>
<td>60 EA</td>
</tr>
<tr>
<td>3</td>
<td>1.00, 0.816, 0.7</td>
<td>0.83</td>
<td>1.47</td>
<td>19.5%</td>
<td>60 EA</td>
</tr>
</tbody>
</table>

Three samples which differ from Nb/Sn ratio and module arrangement were manufactured.

- All samples have similar final filament diameter but Design 1 has more less number of filaments.
- Heat treatment schedule: 225°C-50hr + 410°C-50hr + 650°C-250hr (Ramping rate: 5°C/hr)
- Ta tube were applied for the common diffusion barrier.
Jc measurement was conducted at 16T and 4.2K.
Jc has increased with decreasing diameter, highest Jc, 1,027A/mm², was measured at Design 2 strand.
Remained Sn after reaction is one of the effective parameter that reflects wire performance.
Estimated Ti content in Nb₃Sn filaments is relatively lower than ITER strand(Ti 1.8 at.%).
An intuitive interpretation of the R-billet design was performed to estimate the diffusion behavior.

- Non-uniform distribution of Ti is higher than that of Sn.
- To overcome the limitation of performance, homogeneous Ti diffusion is required.
- Optimization of heat treatment are ongoing to control Ti diffusion.

Poster 2AMSP75
Study on tin and titanium diffusion characteristics for Nb₃Sn strand for FCC conductor

Sn and Ti contents in Nb₃Sn filaments after heat treatment were analyzed by FE-SEM and EDS.
**Development progress**

**Magnetization & RRR measurement results**

<table>
<thead>
<tr>
<th>Wire type</th>
<th>Diameter [mm]</th>
<th>Cu/nonCu</th>
<th>$\mu_0\Delta M@1T$ [mT]</th>
<th>$D_{\text{eff}}$ [$\mu$m]</th>
<th>Sub’t diameter [$\mu$m]</th>
<th>Distance b/w sub’t [$\mu$m]</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 2</td>
<td>0.70</td>
<td>0.92</td>
<td>398.3</td>
<td>155.3</td>
<td>44.2</td>
<td>3.3</td>
<td>197</td>
</tr>
<tr>
<td>Design 3</td>
<td>0.70</td>
<td>0.83</td>
<td>271.6</td>
<td>97.0</td>
<td>42.8</td>
<td>5.2</td>
<td>174</td>
</tr>
<tr>
<td>ITER</td>
<td>0.82</td>
<td>0.98</td>
<td>80.0</td>
<td>79.8</td>
<td>119.6</td>
<td>5.8</td>
<td>120</td>
</tr>
</tbody>
</table>

- RRR values of developed strands show higher values compared to ITER strands. → RRR degradation of ITER strand is associated with the diffusion of Cr plating.
- Design 2 strand have larger magnetization than Design 3 because of smaller distance between sub-elements. → Distance between sub’ts should be increased to reduce the effective diameter.
Plan for performance improvement

Strategy to approach Jc target of FCC

Step 1. Improve Jc with current design
1) Optimization of SnTi arrangement
   (Allocate SnTi spacers on weak diffusion area)
2) Increase Ti contents in SnTi alloy
3) Optimization of heat treatment
4) Opportunity: quality issue of SnTi alloy

Step 2. Design change of Type I
1) Increase number of Nb in the multi-rod
2) Increase number of modules in R-billet
3) Opportunities: Homogeneous distribution of Sn and Ti, Increasing wire breakage

Plan for performance improvement
Conclusions

**Current status of development**

- Achieved $J_c$ with Type I strand - $1,027 \text{ A/mm}^2$@16T, 4.2K
- Exist more room to increase $J_c$ maintaining current design: increase Ti content, Apply SnTi spacers $\rightarrow$ Expected $J_c \sim 1,100 \text{ A/mm}^2$
- Type II and III are faced on drawing issues
- Ta barrier can maintain good RRR performance.
- Effective diameter larger than requirement. $\rightarrow$ Need to consider increasing modules in R-billet

**For the next steps.**

- Need to consider design change of multi assembly and restacking billet to achieve FCC target.
- Proceed manufacturing Type II and III with improved process (HIP + Extrusion $\rightarrow$ Deep hole for SnTi insertion)
- Optimization of heat treatment schedule
Thank you!