# Effect of $Nb_3Sn$ coarse grains on critical current densities of Internal Tin $Nb_3Sn$ strand

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MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

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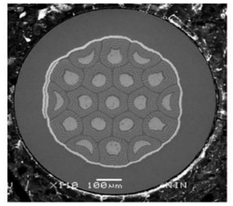
## Background

$Nb_3Sn$ strand have significant applications in constructing high-field (> 10 T) magnets and has great potential value in the next 20 years. Internal-tin (IT) $Nb_3Sn$ strand has been developed by many methods for the future fusion reactor after ITER with low hysteresis loss. However, how to improve the current densities of $Nb_3Sn$ strand has been becoming an important problem with the increasing demand for high $J_c$ $Nb_3Sn$ strand. In our study, we found that more than double Nb content should be added within Internal Tin $Nb_3Sn$ strand and 2 times critical current densities can be enhanced compared with ITER $Nb_3Sn$ strand. With this $Nb_3Sn$ strand, the phase transition during heat treatment was investigated and new phase (Cu-Nb-Sn) can be produced at 400℃ as the reason of more Nb content added and $Cu_6Sn_5$ phase decomposition. The coarse $Nb_3Sn$ grains were analyzed and a composite structure (Cu and $Nb_3Sn$) can be produced as Nb element diffusion during the formation of Cu-Nb-Sn phase. We also found that phase-balance (less Cu-Nb-Sn produced), which can control the formation of $Nb_3Sn$ coarse during filaments, can be obtained through element ratio optimization. With this method, coarse grains among filaments can be refined from micron size into nano-size. Effect of varisized coarse grains on the critical current densities was also studied and we found that micron sized $Nb_3Sn$ (1~2μm) grains reduced the critical current densities severely.

## Experiments

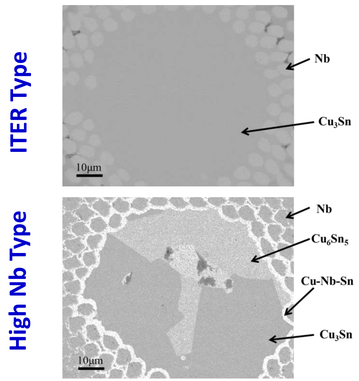
### Parameters and Structure of $Nb_3Sn$ strands



- High Nb content strands were processed through internal-tin $Nb_3Sn$ strand (ITER structure) with 160 Nb filaments. To obtain a high Nb element content, various sizes of Nb rods were used and to enlarge the Nb volume. The Cu/Nb composite rod was obtained from Cu/Nb billet after hot extrusion. Then the composite rod was drilled by deep-hole drilling machine. Sn-2wt.%Ti alloy rod was inserted into the Cu/Nb composite tube and the subelements were prepared after drawing and shaping. Ta tube was selected as the barrier to prevent Sn from diffusing into the Cu stabilizer. Final billet was assembled by stacking 19 subelements into Ta and Cu tubes. The final billet was drawn, twisted and calibrated, and then the final strand with 0.82 mm and 0.3 mm was obtained. The ratio of Cu/ non-Cu is close to 1.0.

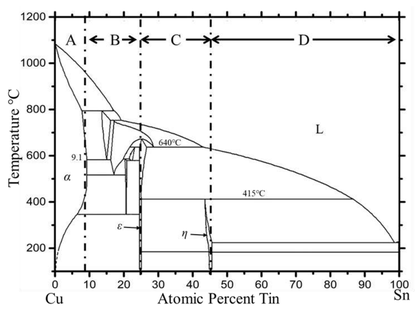
## Results

### *Phase transition during Heat treatment (400 ℃-50h)*



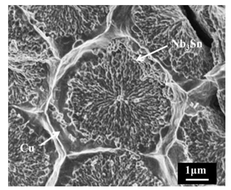

- $Cu_3Sn$ （76.05at.% Cu and 23.95at.% Sn）was found within ITER type strand after a heat treatment (400℃-50h).
- $Cu_3Sn$, $Cu_6Sn_5$ and Cu-Nb-Sn phase (16.34at.% Cu, 21.12at.% Nb and 62.54at.% Sn, $(Nb_{0.75}Cu_{0.25})Sn_2$) was formed within the high Nb content type strand after a heat treatment (400℃-50h).
- Cu-Nb-Sn phase distributed around Nb filaments and Cu/Nb/Sn interdiffusion occured during the heat treatment.

### *Effect of Sn/Cu ratio on phase transition*

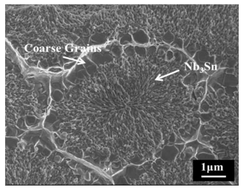



- The Sn-Cu phase diagram can be divided into four parts combined with the thermostability of different SnCu phase with various types of $Nb_3Sn$ strands. With the increasing of Nb content, high Sn/Cu ratio can be found within various types of $Nb_3Sn$ strand.
- In part A and part B (for bronze $Nb_3Sn$ and ITER $Nb_3Sn$), α-Cu and CuSn phase showed high thermal stability below 700℃.
- In part C and part D (for high $J_c$ $Nb_3Sn$ strand), liquid Sn can be produced as the decomposition of $Cu_6Sn_5$ around 400 ℃ and melting of Sn. Cu-Nb-Sn phase formation can be induced as the exist of liquid Sn.

### *Microstructure and coarse grains formation (665 ℃-100h)*



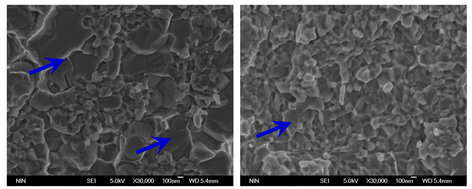

**ITER Type**
**1046A/mm²@4.2K, 12T**



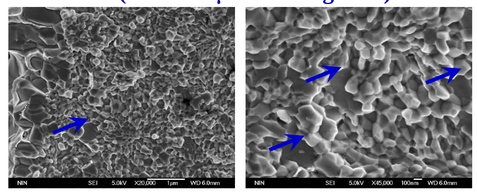

**High Nb Type**
**1635A/mm²@4.2K, 12T**

- Different phases can be induced with 400℃-50h—665℃-100h heat treatment.
- Coarse grains containing copper and discrete $Nb_3Sn$ phase (70.22at.% Cu, 21.06at.% Nb, 8.7at.% Sn) can be found surrounding Nb filaments.
- As the formation of Cu-Nb-Sn phase, Cu-Nb interdiffusion taken out and micro-szie diffusion distance was induced from Nb filaments. Compared with nano-sized $Nb_3Sn$ grains, the distance among $Nb_3Sn$ grians is too large to transfer current.

### *Effect of coarse grains on current density*



**1877A/mm²@4.2K, 12T**
**(with 1~2 μm coarse grains)**



**2122A/mm²@4.2K, 12T**
**(with 300~400nm coarse grains)**

- Coarse grains can be refined through Cu reduction among Nb filaments with elements diffusion.
- A big impact of Grain size of Cu/$Nb_3Sn$ mixture on the performance of high $J_c$ $Nb_3Sn$ strand can be found.
- With the nano-sized grains, $J_c$ about 2122A/mm² (@4.2K, 12T) can be obtained.

## Conclusions

- Compared with standard strands, various CuSn phases can be produced after a heat treatment of 400℃-50h.
- Cu-Nb-Sn phase, which was induced as the high ratio of Sn/Cu as the reason of high Nb content.
- For the high Nb content strand, coarse grains containing $Nb_3Sn$ and Cu, can be found around Nb filament.
- With the formation of Cu-Nb-Sn phase, interdiffusion between Nb and Cu indcued the coarse grain formation.
- Increasing the Nb content and reduction of copper around Nb filaments, coarse $Nb_3Sn$ grains can be eliminated and high $J_c$ can be obtained.
- With the nano-sized grains, $J_c$ about 2122A/mm² (@4.2K, 12T) can be obtained.

Presented at the MT-26, 2019 Sep. 22 – Sep.27, Vancouver, Canada; Poster No.: MT26-Wed-Af-Po3.21-10[76]