Novel Pb- and Cd-free superconducting joint between NbTi and Nb_3Sn wires using high-temperature-tolerable superconducting Nb-alloy intermedia

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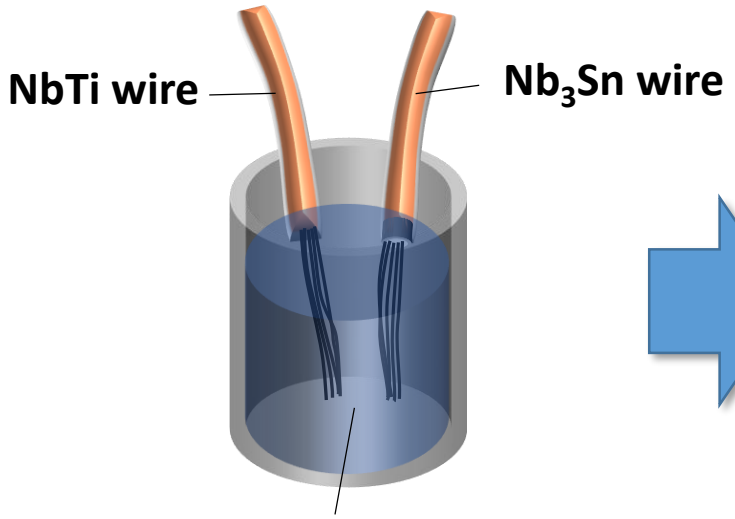
Abstract

Conventional technique

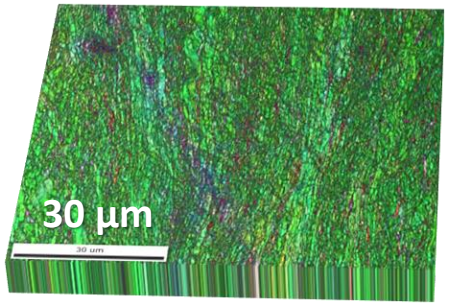


Pb-alloy superconducting solder

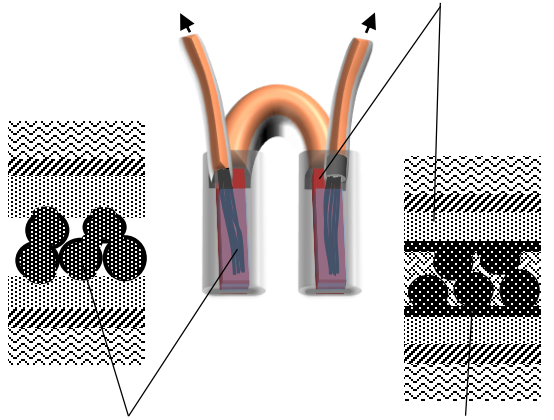
Pb–Bi alloy and Wood's metal have been used for more than 30 years as representative superconducting solder intermedia to establish superconducting joints between NbTi and Nb_3Sn wires. **However, the use of Pb and Cd has been severely restricted by environmental regulations**.

New method for SC joint between NbTi and Nb_3Sn

High temperature tolerable (HTT) Superconducting Nb–alloy



800 °C x 3 h



The key point is to use a high-temperature-tolerable (HTT) superconducting Nb-alloy as an intermedia, whose critical current does not deteriorate even after exposure to temperatures higher than 650 °C.

Nobuya Banno et al., "High-temperature-tolerable superconducting Nb-alloy and its application to Pb- and Cd-free superconducting joints between NbTi and Nb_3Sn wires", **Journal of Materials Science, (2021),** https://doi.org/10.1007/s10853-021-06585-8, **Open Access**

Difficulties in the Pb-free joint (1)

1. Difficulty of development of alternative Pb-free solder

Candidate material: **In-Sn-based alloy**

- Lower B_{c2} : ~0.2 T
- No report on the successful formation of superconducting joint between NbTi and Nb_3Sn wires

1. Levy SA, Kim YB, Kraft RW (1966) Effect of structure on the superconducting properties of eutectic alloys. J Appl Phys 37:3659–3665. https://doi.org/10.1063/1.1707901
2. Mousavi T, Aksoy C, Grovenor CRM, Speller SC (2016) Microstructure and superconducting properties of Sn-In and Sn-In-Bi alloys as Pb-free superconducting solders. Supercond Sci Technol 29:015012. https://doi.org/10.1088/0953-2048/29/1/015012
3. Santra S, Davies T, Matthews G, et al (2019) The effect of the size of NbTi filaments on interfacial reactions and the properties of InSn-based superconducting solder joints. Mater Des 176:107836. https://doi.org/10.1016/j.matdes.2019.107836

Difficulties in the Pb-free joint (2)

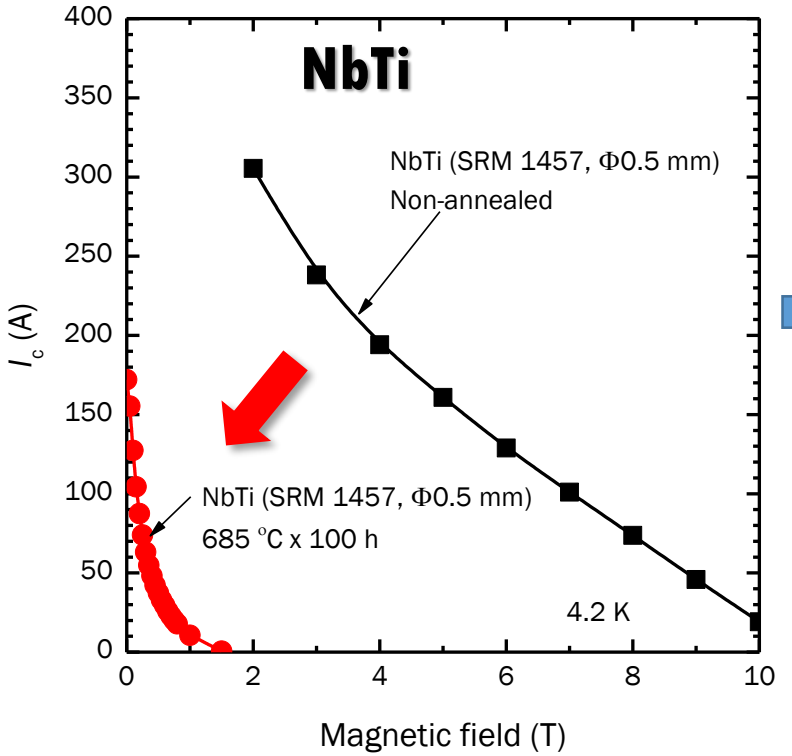
2. Mechanical property of Nb_3Sn

NbTi: Body-centered-cubic alloy → ductile

Nb_3Sn: compound superconductor → brittle

Mechanical pressing cannot be applied.

3. Rapid deterioration of the superconducting properties of NbTi after exposure to high temperatures



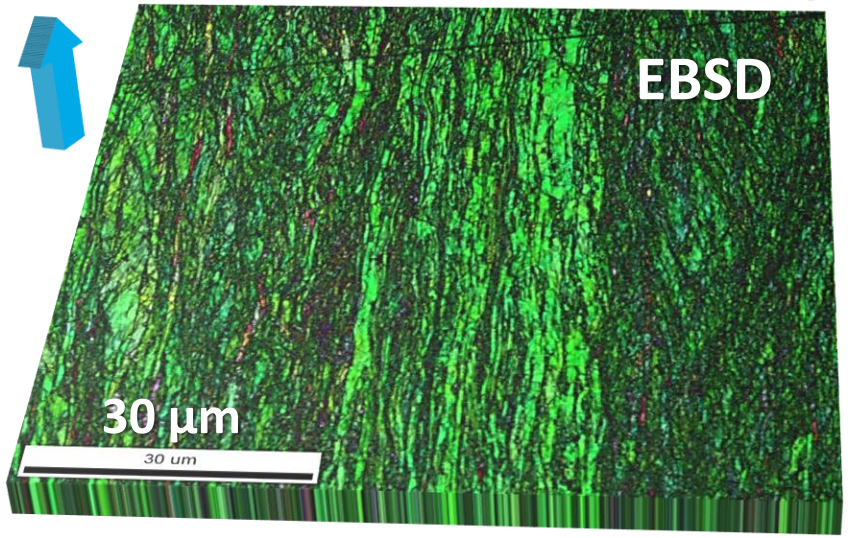
High temperature chemical reaction process cannot be applied.

How can we solve the problem?

Development and use of a high-temperature-tolerable (HTT) Nb-alloy as intermedia

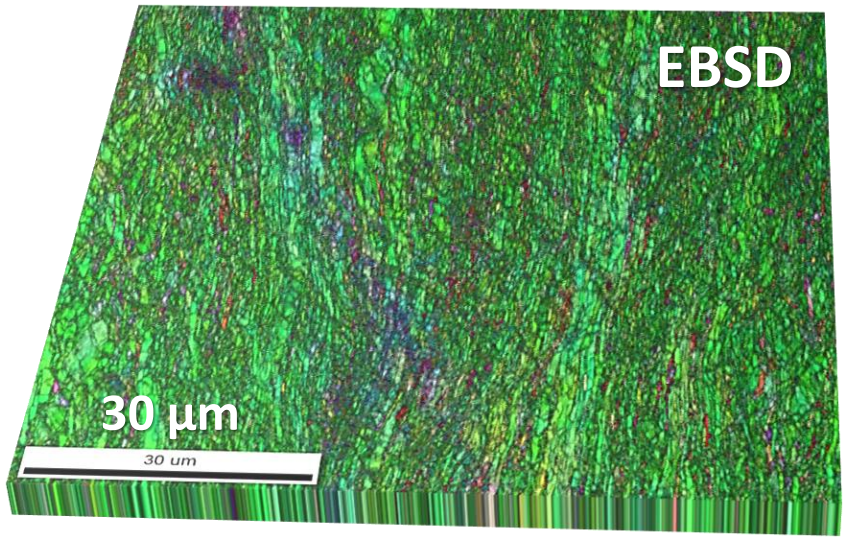
Ex.) Nb-4Ta-Hf

Rolling direction

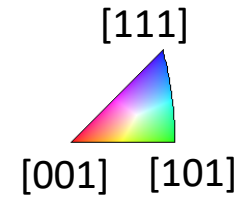


As-deformed

Still fine



800 °C x 3 h

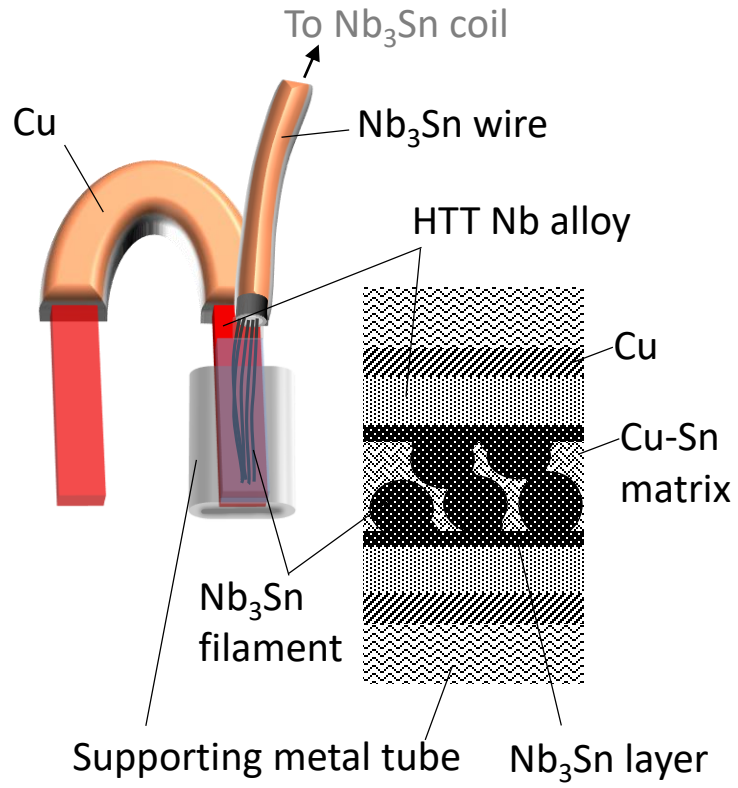


→ That enables a chemical reaction between Nb_3Sn and HTT Nb-alloy, and a mechanical bonding between HTT Nb-alloy and NbTi.

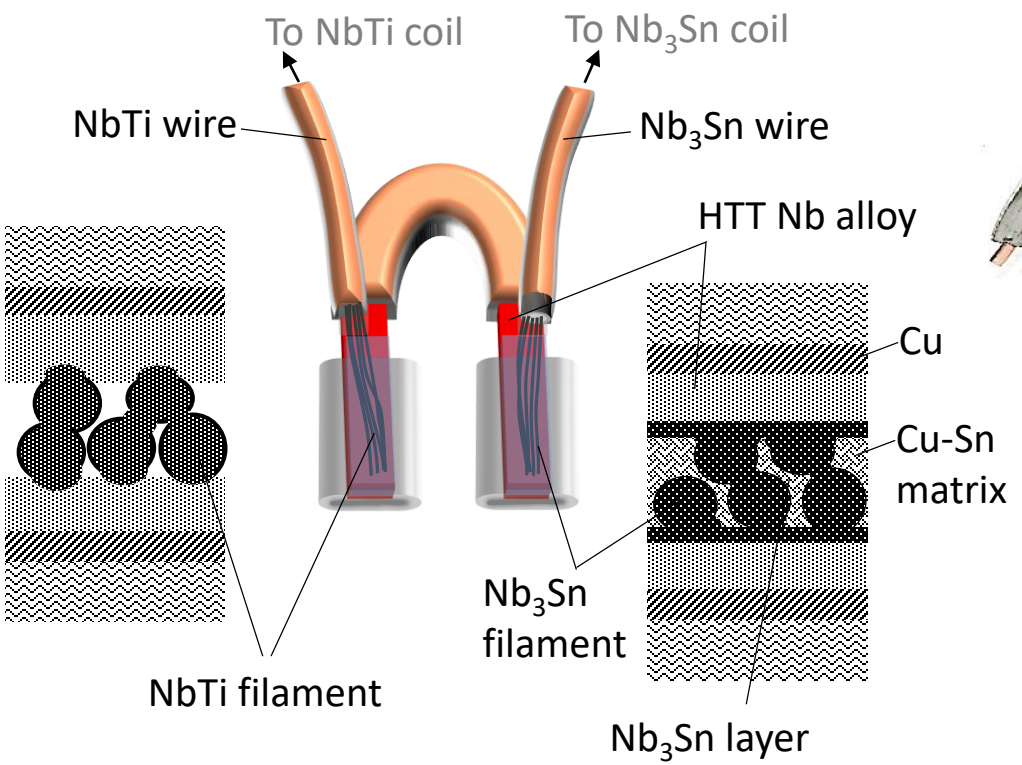
The purpose of this work

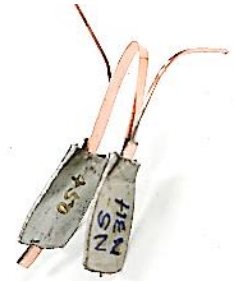
Method

STEP-1:
Joint between Nb_3Sn and HTT Nb-alloy



STEP-2:
Joint between NbTi and HTT Nb-alloy

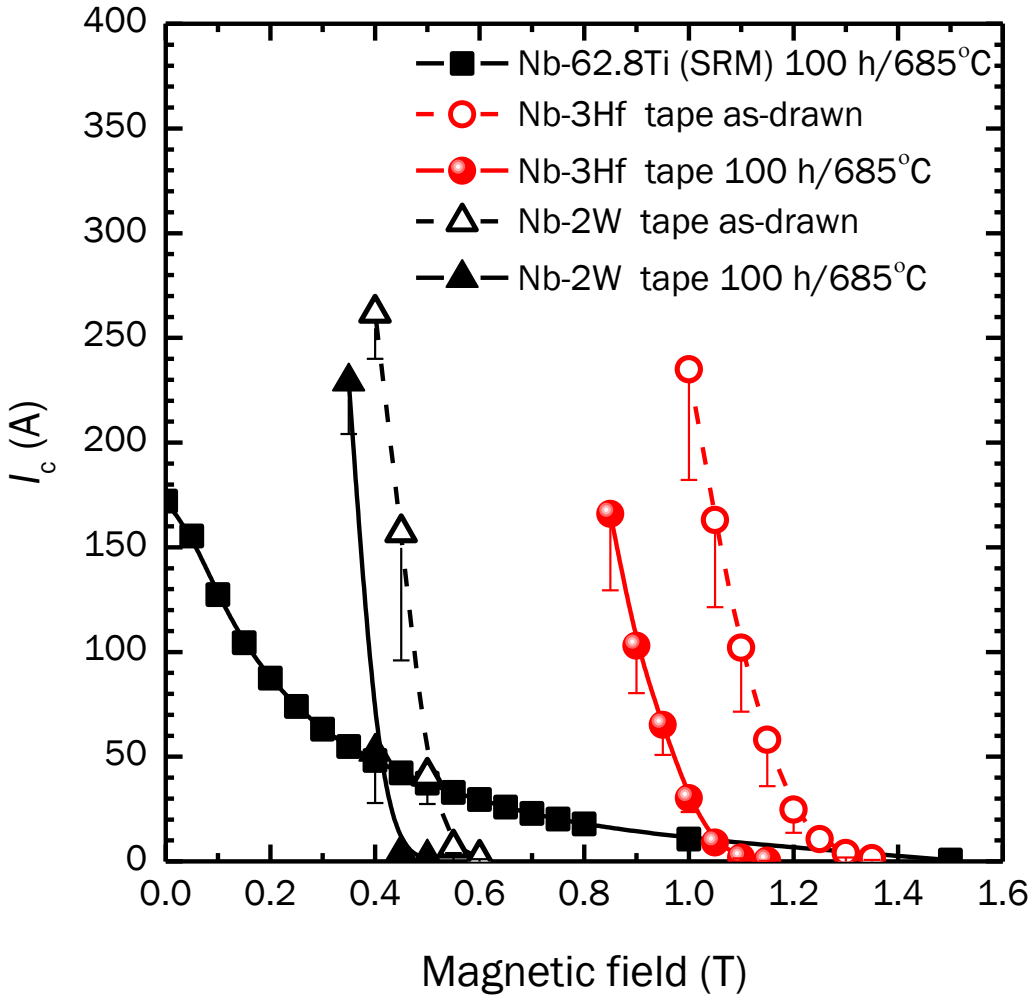




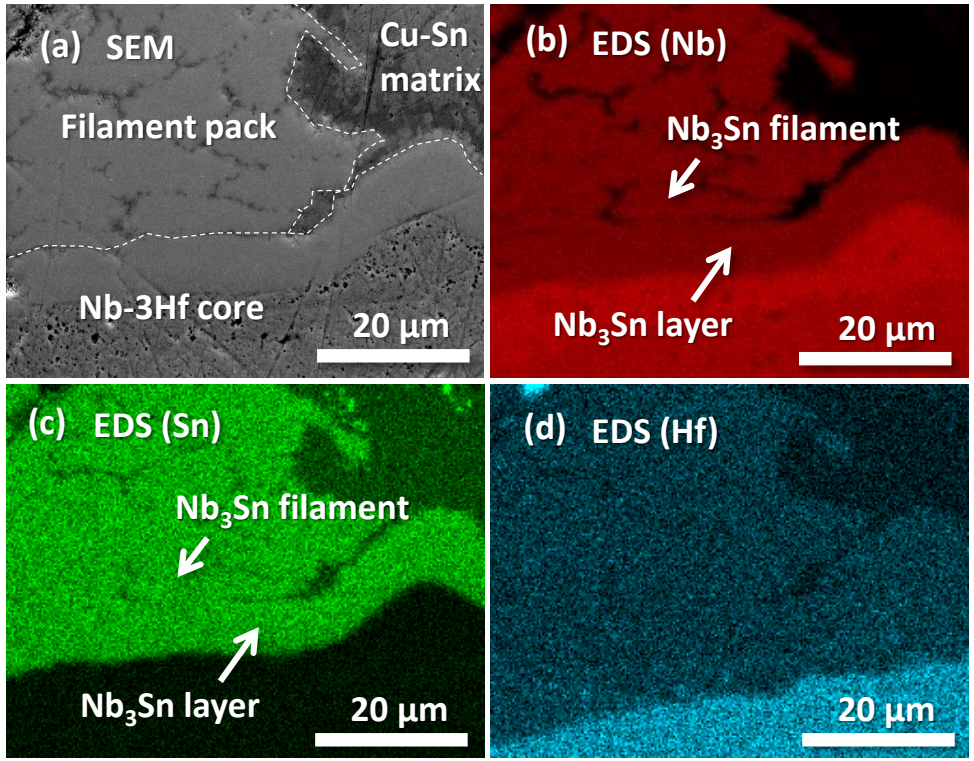
Candidate additives to Nb and I_c properties

	4B	5B	6B
	–62.8Ti	V	Cr
B_{c2}	11.5 → 1.5 T		
I_c	37.4 A@0.5 T		
n	32 @0.5 T		
	–5Zr	**Nb**	Mo
B_{c2}	2 T (ref.) → not measured	0.41 → 0.31 T	
I_c	No data	31 A@0.25 T	
n	No data	46 @0.25 T	
	–3Hf	**–4Ta–1Hf**	**–2W**
B_{c2}	1.35 → 1.15 T	0.8 → 0.62 T	0.65 → 0.52 T
I_c	65 A@0.95 T	149 A@0.5 T	229 A@0.35 T
n	65 @0.95 T	125 @0.5 T	60 @0.35 T

*B_{c2}: values before and after annealing at 685 °C × 100 h.
**I_c and n: values after annealing at 685 °C × 100 h.

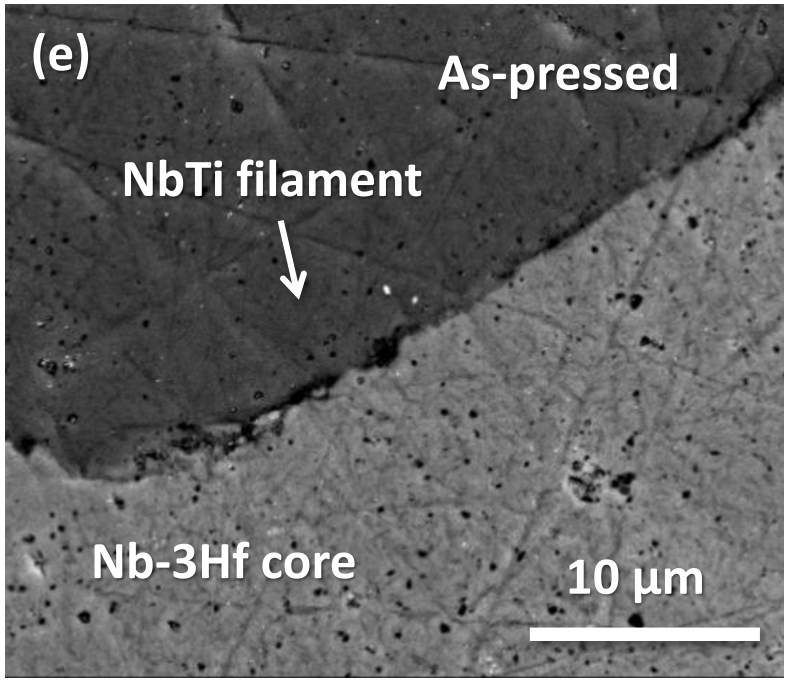


Results – microstructure of joint –



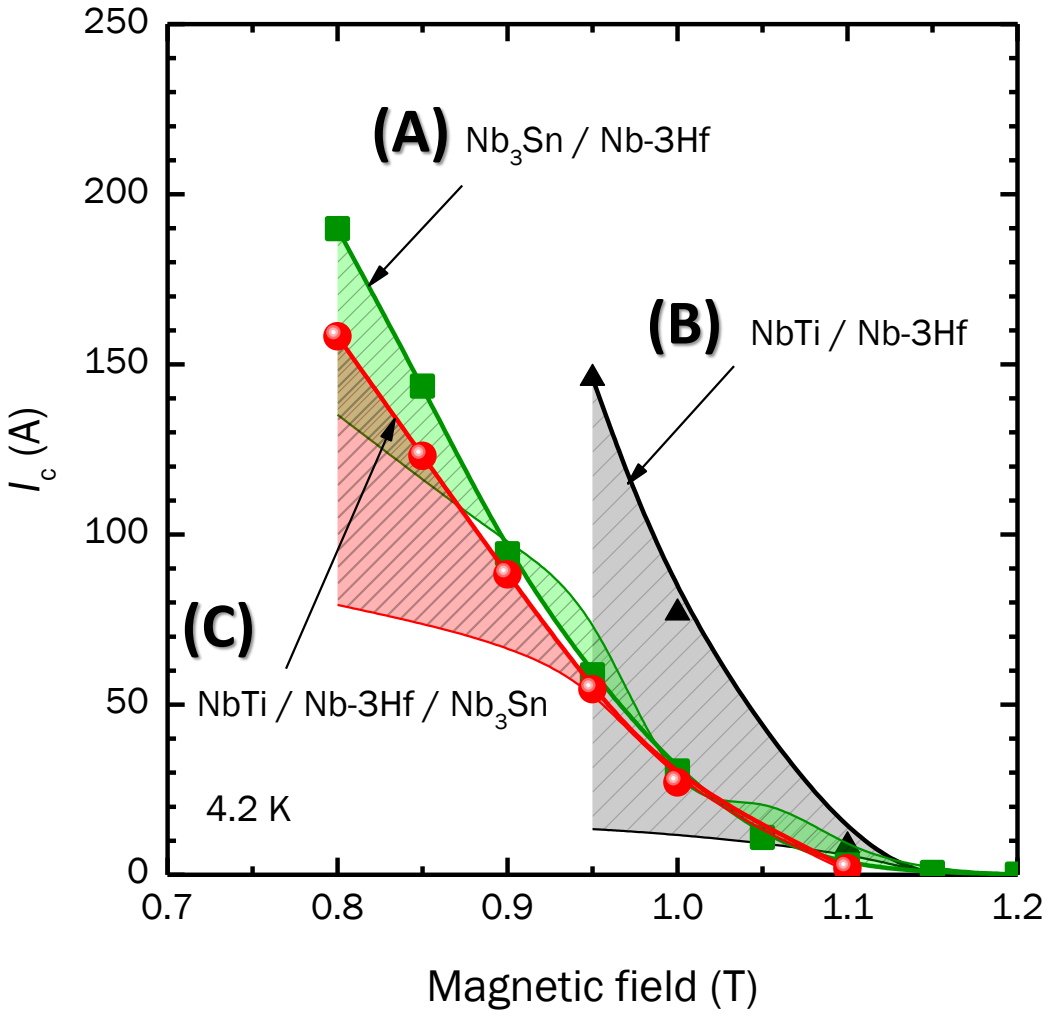
Boundary between Nb_3Sn and Nb-3Hf

Formation of Nb_3Sn layer



Boundary between NbTi and Nb-3Hf

Results – I_c characteristics of joint –



Joint A:

- Steep I_c–B curve (I_c@0.8 T > 150 A)
- **Importantly, the yield rate ~ 100%**
- Scattering of the I_c data of the joints was so small.

Joint B:

- Some of the specimens: very good
- **a few samples of joint : low I_c characteristics**.

Joint C:

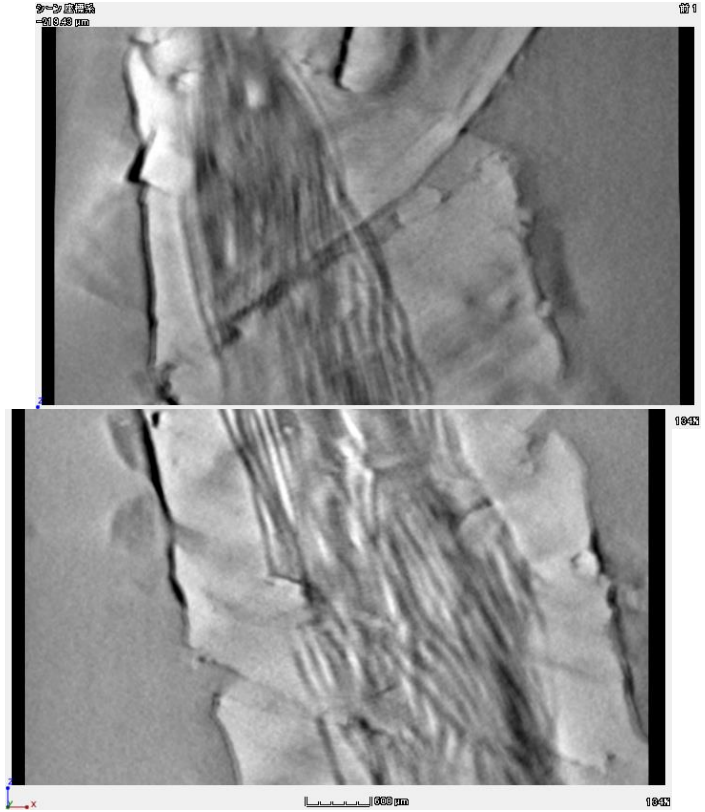
- Almost specimens: good
- **Some of the I_c data : scattered similar to joint B**, probably reflecting from quality of joint B

Results – reasons for low I_c –

- **Breakage of NbTi filaments in cold-pressing**

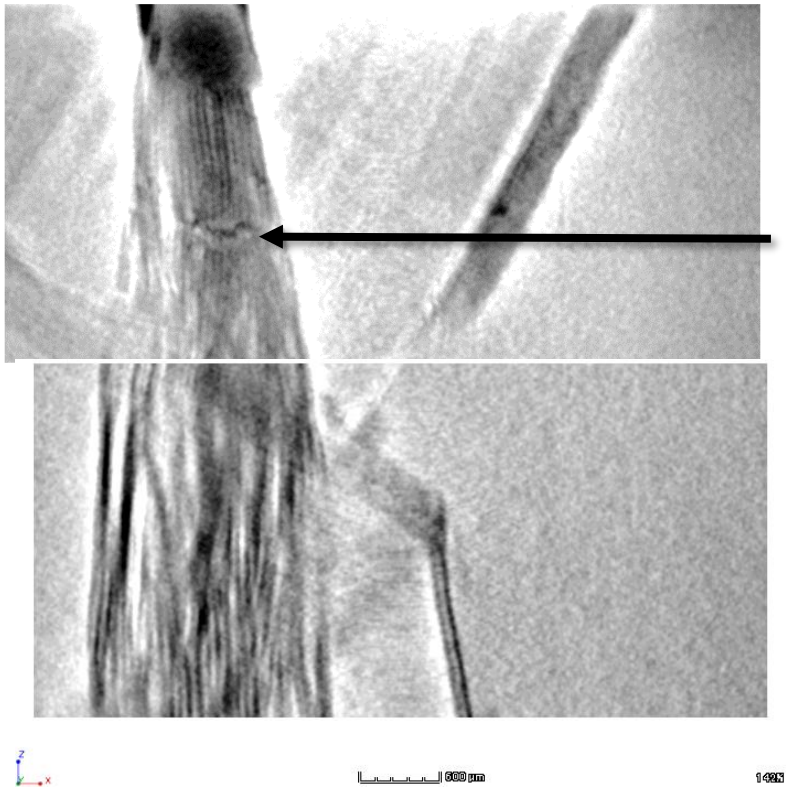
X-ray CT scan for NbTi / Nb-3Hf joint

Excellent sample



No filament damage is observed.

Bad sample

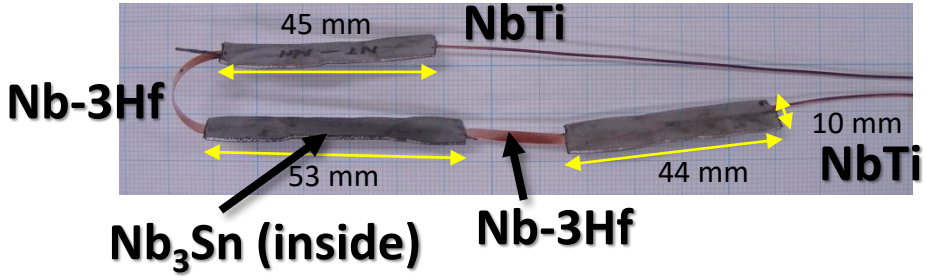


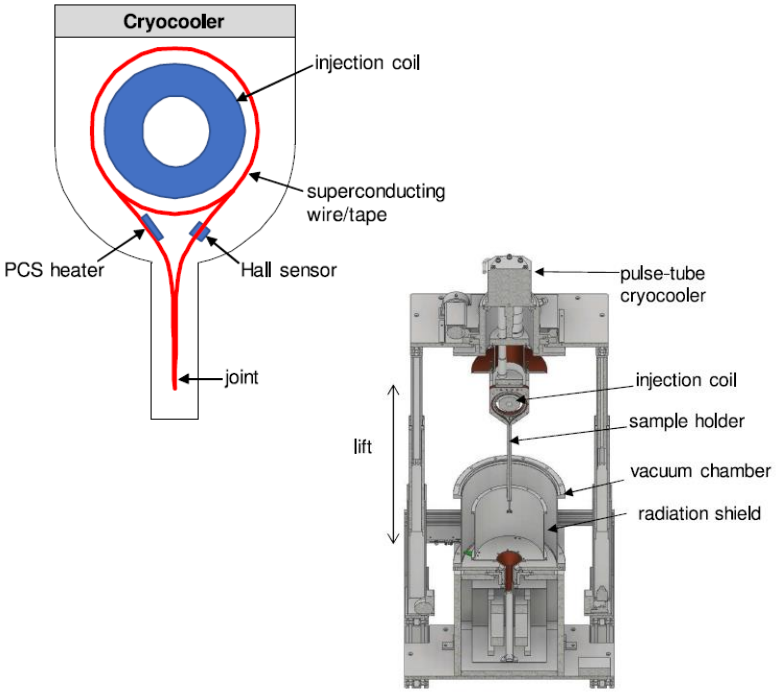
Filament breakage

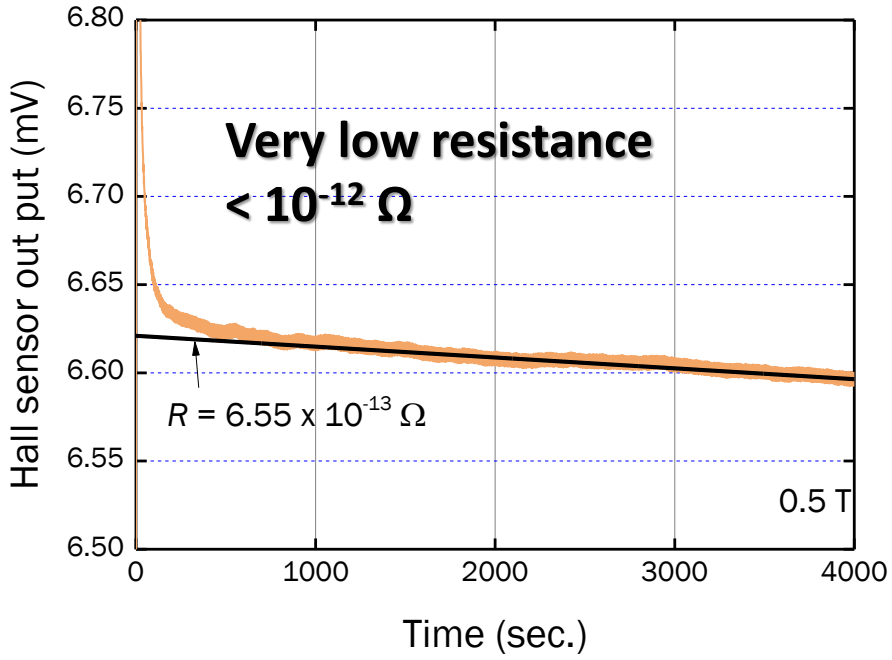
Results – Joint resistance –

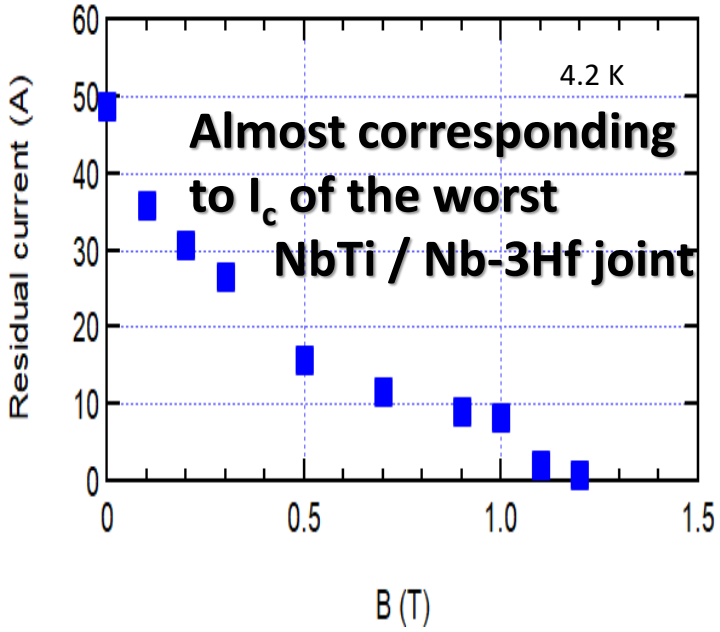
Current decay measurement

to evaluate the ultra-low joint resistance, and to confirm the formation of the superconducting joint









Kobayashi K, Nishijima G, Uchida A, et al (2020) Development of a superconducting joint resistance evaluation system. IEEE Trans Appl Supercond 30:10–13. https://doi.org/10.1109/TASC.2020.2967680

The residual currents were small.

← Due to filament damage

Conclusions

- The author developed superconducting Nb alloy intermedia whose critical current does not decrease even after exposure to high temperatures. Based on this Nb alloy, a new concept for metallurgically realizing completely Pb- and Cd-free superconducting joints between NbTi and Nb_3Sn wires was proposed and proven experimentally.

- Hf is the most suitable additive for realizing HTT superconducting Nb-alloy intermedia.

- The B_{c2} value of Nb–3 at%Hf alloy was 1.15 T even after an Nb_3Sn layer formation at 685 °C. The B_{c2} has not been optimized yet.

- The yield rate of the successful superconducting joints between Nb_3Sn wire/Nb–3Hf tape was 100%.

- I_c of NbTi/HTT Nb-alloy joints shows a relatively larger scattering tendency at the moment.

- Optimization of the cold-pressing method, its pressure and the joint length would be needed in order to improve the yield rate of high quality joint, especially for NbTi/HTT Nb-alloy joint.