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Thermal conductivity of NI HTS coil fabricated by diffusion bonding technique

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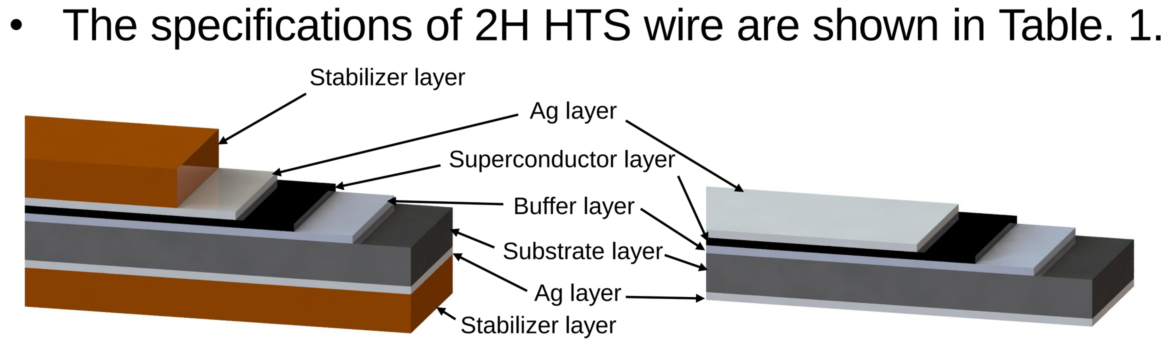
Introduction

- The thermal contact resistance between winding turns of the no-insulation (NI) high temperature superconducting (HTS) coil is not clearly known because the HTS wire has various surface conditions such as roughness and oxidation.
- In this study, the diffusion bonding (DB) technique using Ag is applied to make expectable contact resistance between turns of the NI HTS coil.
- The thermal conductivity of the NI coil are measured in a conduction cooling experimental apparatus applying heat loads to the outside of coil.

Experimental conditions

- For the NI coil, a 2G HTS wire is used which has silver layer processed by sputter on the outermost, as shown in Fig. 1.
- The specifications of 2H HTS wire are shown in Table. 1.



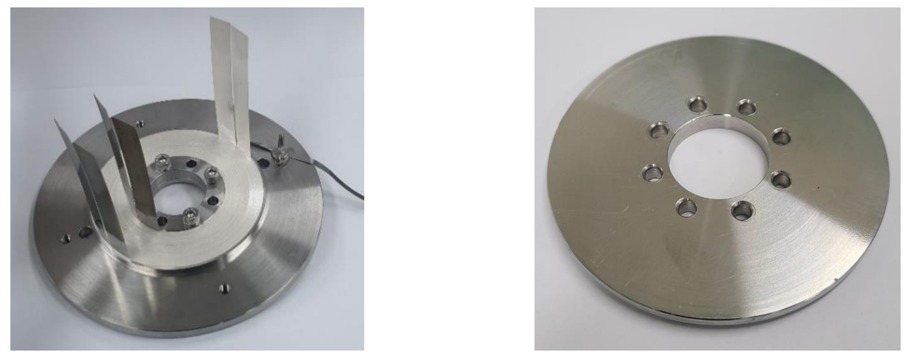
(a) General 2G HTS wire (b) 2G HTS wire for diffusion bonding

Fig. 1. Shape of 2G HTS wire

Table. 1. Specifications of 2G HTS wire

Thickness	Width
0.11 [mm]	4.08 [mm]

- Winding a small coil on a STS bobbin using the Ag sputtered 2G HTS wire.
- After winding, the NI coil was heat treated at 600 ℃ × two hours, 1atm O_2 for DB, as shown in Fig. 2.
- Stainless steel (STS) 304 block of the similar size and shape to the coil was manufactured to verify the measured thermal conductivity of the NI coil, as shown in Fig. 2.
- The specifications of the NI coil and STS 304 block are shown in table. 2.



(a) DB coil (b) STS 304 block

Fig. 2. Shape of DB coil and STS 304 block

Table. 2. Specifications of DB coil and STS 304 block

List	DB coil	STS 304 block
Inner radius [mm]	25	15
Outer radius [mm]	44.47	50
Number of turns	177	-
Winding tension [kgf]	3	-

- The temperature differences for calculating thermal conductivity were measured from 20 to 77 K and three heating conditions (0.28 W, 0.57 W, 1.1 W)
- The experimental setup is shown in Fig. 3.
- The calibrated temperature sensors (PT-100) was used, and the measurement error was less than 50 mK.
- The radial positions of temperature sensor are shown in table. 3.

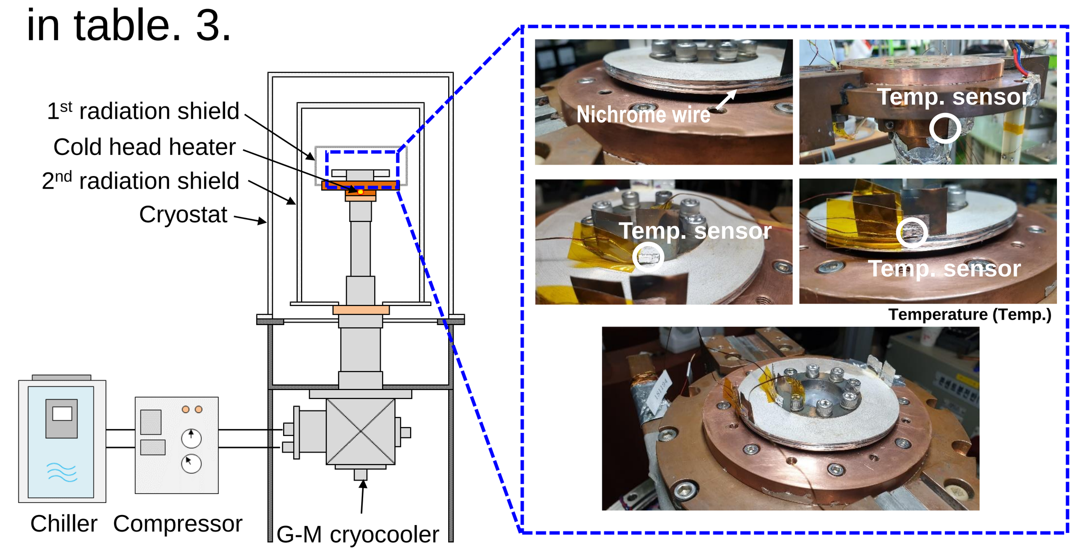


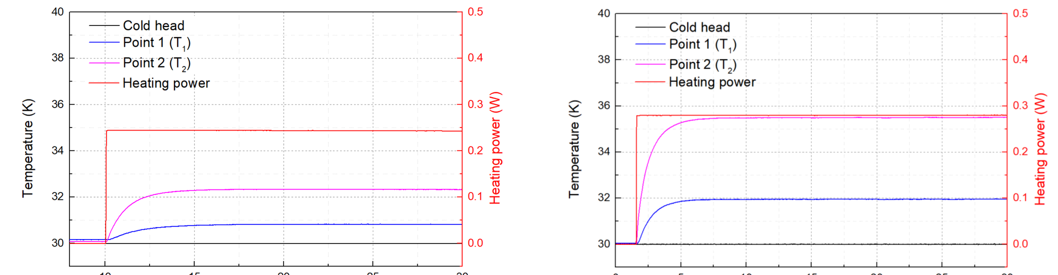
Fig. 3. Experimental setup

Table. 3. Radial position of temperature sensor

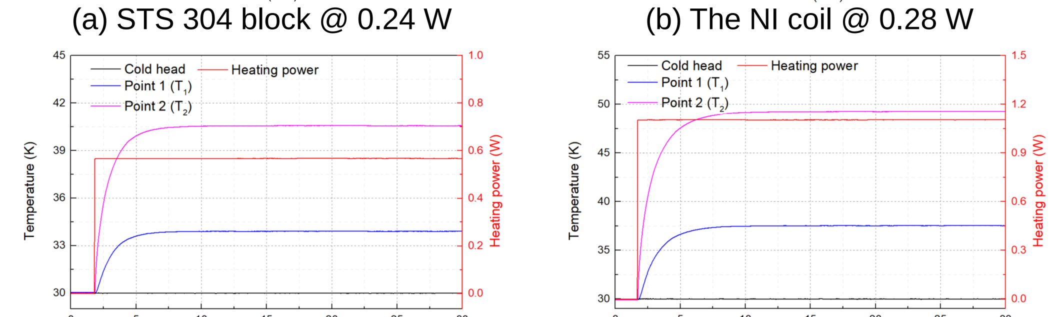
	NI coil	Stainless steel block
Point 1	25.33 [mm]	25.1 [mm]
Point 2	44.47 [mm]	45.1 [mm]

Experimental results

- The temperature variations according to the applied heating to the NI coil and STS 304 block are shown in Fig. 4.
- The temperature differences at each reference temperature are shown in table. 4.



(a) STS 304 block @ 0.24 W (b) The NI coil @ 0.28 W



(c) The NI coil @ 0.57 W (d) The NI coil @ 1.1 W

Fig. 4. Temperature distributions of the NI coil and STS 304 block at 30 K

Table. 4. Reference and difference temperature depending on heating power

Heating power 0.28 W		Heating power 0.57 W		Heating power 1.10 W	
Reference Temperature	$T_2 - T_1$	Reference Temperature	$T_2 - T_1$	Reference Temperature	$T_2 - T_1$
24.87 K	4.57 K	28.96 K	8.19 K	35.70 K	13.48 K
29.17 K	3.99 K	32.93 K	7.37 K	39.36 K	12.47 K
33.74 K	3.55 K	37.25 K	6.66 K	43.33 K	11.62 K
38.46 K	3.20 K	41.80 K	6.12 K	47.51 K	10.97 K
48.12 K	2.73 K	51.17 K	5.32 K	56.50 K	9.75 K
57.89 K	2.42 K	60.71 K	4.77 K	65.68 K	8.80 K
67.62 K	2.19 K	70.24 K	4.35 K	75.06 K	8.22 K
79.48 K	2.02 K	81.81 K	4.01 K	86.40 K	7.61 K

Discussion

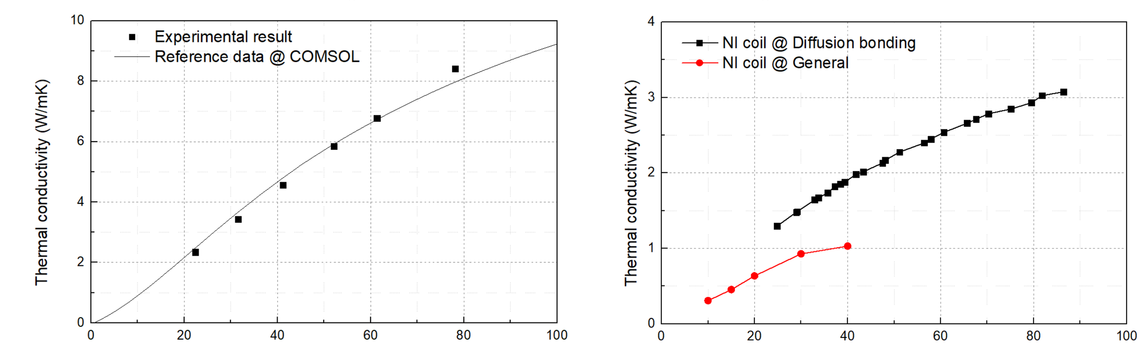
- The thermal conductivity is calculated by (1) - (3).

$$\dot{Q} = \frac{T_2 - T_1}{R_{total}} \quad (1) \qquad R_{total} = \frac{\ln(\frac{r_o}{r_i})}{2\pi k W} \quad (2)$$

$$k = \frac{\ln(\frac{r_{outerlayer}}{r_{innerlayer}})}{2\pi W R_{total}} \quad (3)$$

$\dot{Q}$ = heating power
R_{total} = overall thermal resistance
k = thermal conductivity
W = width of 2G HTS wire
r_i and r_o = inner and outer radius of coil.

- As shown in Fig. 5 (a), the measured thermal conductivity of STS 304 block was found to agree with the reference value [1].
- As shown in Fig. 5 (b), the thermal conductivity of the NI coil was higher than that of the general NI coil [2].



(a) Thermal conductivity of STS 304 block [1] (b) Thermal conductivity depending on type of NI coil

Fig. 5. Measured thermal conductivity of the NI coil and STS 304 block

Table. 5. Specification of 2G HTS wire cross section

	Substrate	Superconductor	Ag (upper)	Ag (lower)	Ag (right edge)	Ag (left edge)
Thickness [um]	97.7	3.43	5.15	3.72	-	-
Width [mm]	4.0743	4.0743	4.0743	4.0743	0.0057	0.0057

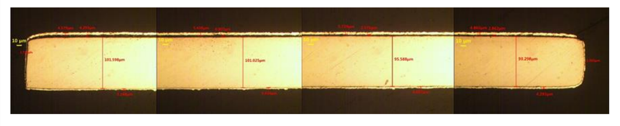


Fig. 6. Cross section of 2G HTS wire

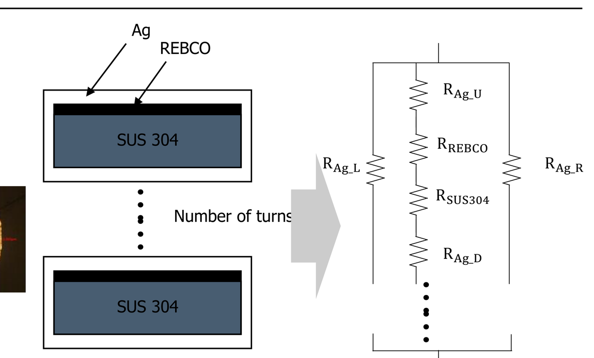


Fig. 7. TRC

- The k was calculated by reference value to compare the measured k and the theoretical k [1, 3], and the cross section of 2G HTS wire and the thermal resistance circuit (TRC) are shown in table. 5, Fig. 6, and Fig. 7 assuming perfect contact between winding turns.
- Compared to the theoretical value, the measured value was found to be about 20 – 30% smaller as shown in Fig. 10.
- Decreased thermal conductivity seems to be from the imperfect contact between winding turn after DB as shown in Fig. 8.

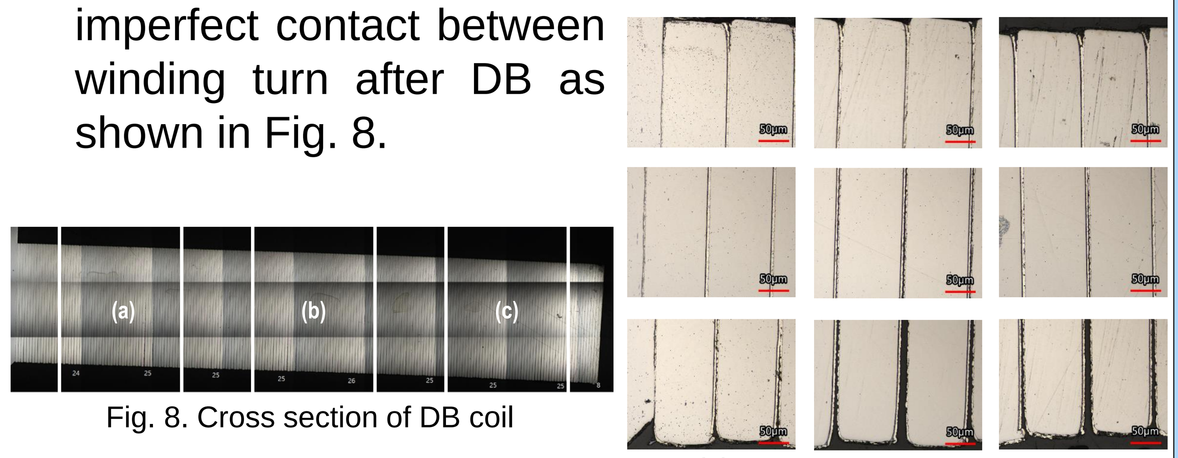


Fig. 8. Cross section of DB coil

(a) (b) (c)

- It is found that the bonding of the silver at the edge was not smooth, and that the bonding on the interface of the 2G HTS wire was about 1/3.
- As shown in Fig.9, according to the degree of DB, Ag on both sides of the TRC was removed and the center resistance increased by three times.
- As a result, the modified theoretical value is similar to the experimental measurement value, as shown in Fig. 10.

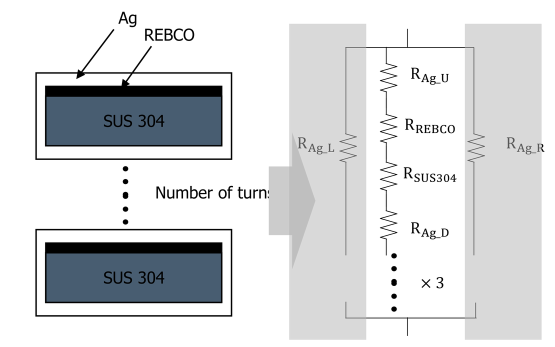


Fig. 9. Modified TRC

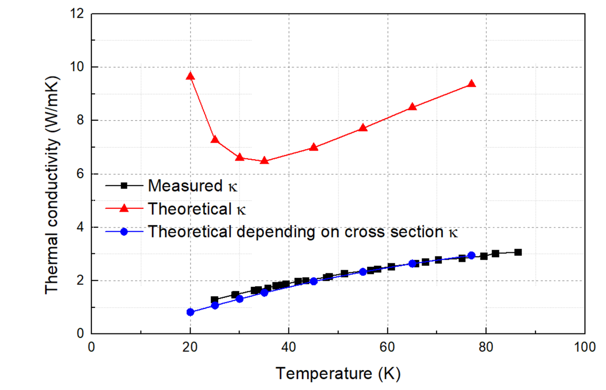


Fig. 10. Measured and theoretical k

Summary and Conclusion

- In this paper, Ag DB was proposed as a new winding technique for a NI coils.
- The key to the new winding technique is to predict the thermal conductivity of the NI coil by removing the turn to turn interface.
- In order to confirm the new technique, a thermal conductivity experiment was performed by fabricating a the NI coil and an STS 304 block.
- The thermal conductivity of the NI coil and STS 304 block were measured from 20 to 77 K in the conduction cooling experiment.
- As a result, the measured thermal conductivity was different from the theoretical value assuming perfect contact.
- This result shows that the interface of the 2G HTS wire is not fully in bonding with DB, and if the bonding is completely performed by improving the DB process in the future, it is determined that the thermal conductivity could be predicted from a theoretical value.

Reference

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