Effect of thermal cycle and winding tension on contact resistivity of an intra-Layer No-insulation (LNI) REBCO coil

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1. Background and Objective

- The intra-Layer No-Insulation (LNI) method provides self-protecting characteristics from a quench, which are useful for a high-current density REBCO layer-wound coil.
- An LNI coil has an electrical contact resistivity, ρ_{ct}, between inter-layer copper sheets and the facing conductors, and this parameter drastically affects quench behavior.
- In previous work, an LNI-REBCO coil was happened to be protected from a 31.4 T quench at a high ρ_{ct} value of 10,000 μΩcm², while the ρ_{ct} value was changing through the series of thermal cycles, charging tests and quenches [1].
- It is of great importance to control the value of ρ_{ct} for designing the protection scheme of an LNI-REBCO coil.

[1]Y Suetomi et al. SUST. 34 (2021) 064003

The objective of the present study:

To obtain basic knowledge for the behavior of ρ_{ct} values of LNI-REBCO coils via the following experiments.

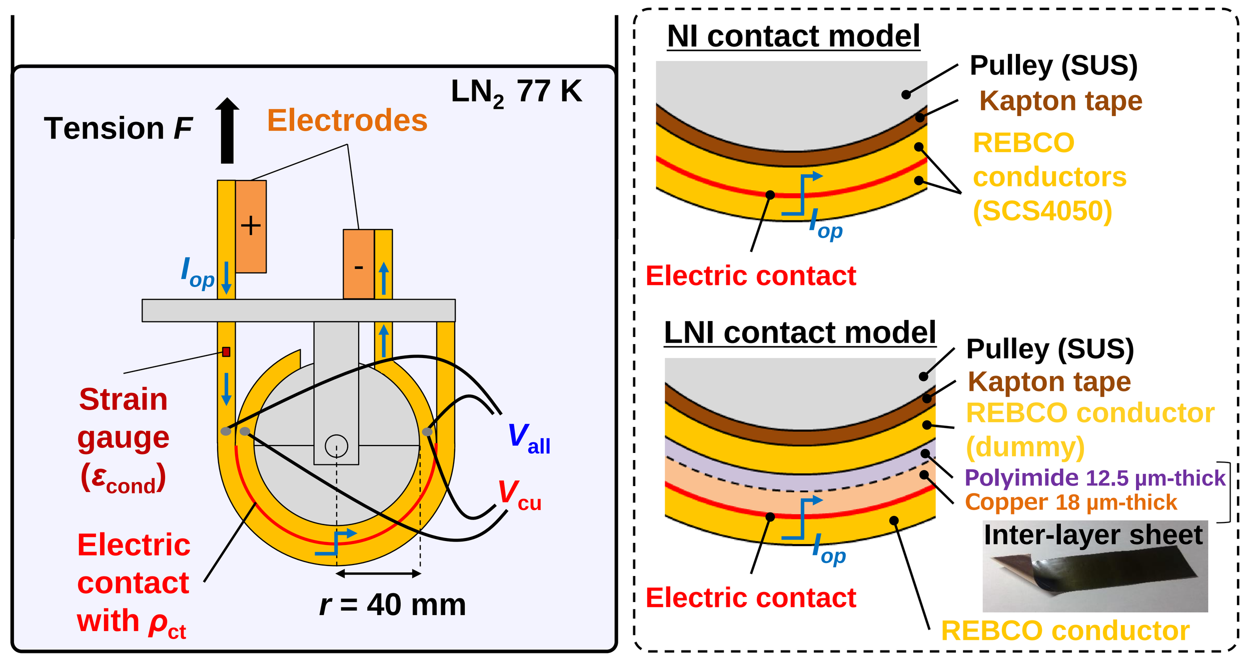
(A) Contact model experiment, investigating the effects of the contact pressure on ρ_{ct} values.

(B) Coil experiment, investigating the effects of winding tensions and thermal cycles on ρ_{ct} values.

2. Contact model experiment

2-1. Experimental setup

[2] W. Denis Markiewicz et al. IEEE. 22(2012) 4300704



Tension F:

$$F\ [\mathrm{N}] = \varepsilon_{cond} E_{cond} w t$$

Contact pressure:

$$P_{contact}\ [\mathrm{Pa}] = \frac{F}{wr}$$

F : tension
ε_{cond} : strain
E_{cond} = 130 (GPa)[2] : Young's modulus
w : conductor width
t : conductor thickness
g : gravitational acceleration
$P_{contact}$: contact pressure
r : pully's radius

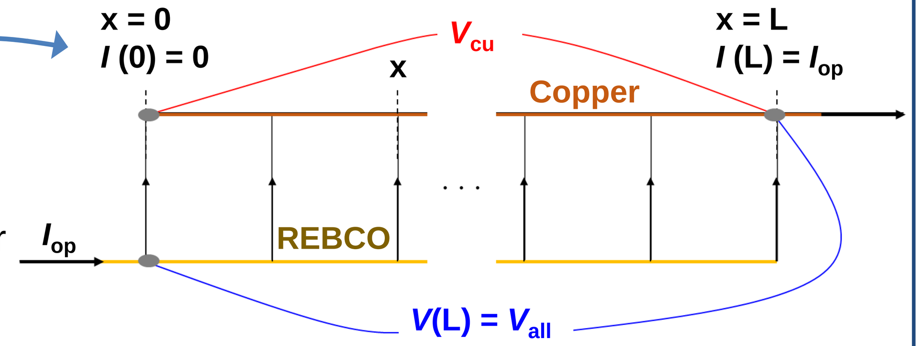
2-2. Method to estimate the value of ρ_{ct}

NI contact model

$\rho_{ct} = V_{all} / I_{op} \times \pi r w$

LNI contact model

Current transfer [3] between the REBCO conductor and the copper sheet are considered using the following equation.



$$V(x) = r_{ct}\frac{dI(x)}{dx} \quad \cdots (1)$$

$$\frac{dV(x)}{dx} = I(x) r_{cu} \quad \cdots (2)$$

$$r_{cu} = \rho_{cu}/S_{cu},\ r_{ct} = \rho_{ct}/w$$

Eqs. (1) and (2) give

$$V(x) = \frac{1}{\alpha^2}\frac{d^2V(x)}{dx^2} \quad \cdots (3) \quad \left(\alpha = \sqrt{\frac{r_{cu}}{r_{ct}}}\right)$$

Boundary conditions: $I(0) = 0 \quad I(L) = I_{op}$

$$V(x) = I_{op}\sqrt{r_{cu} r_{ct}}\frac{e^{\alpha x} + e^{-\alpha x}}{e^{\alpha L} - e^{-\alpha L}}$$

$$I(x) = I_{op}\frac{e^{\alpha x} + e^{-\alpha x}}{e^{\alpha L} - e^{-\alpha L}}$$

r_{cu} : In-plane resistance of the copper sheet per unit length
$\rho_{cu} = 2.05 \times 10^{-9}$ (Ωm) : copper sheet resistivity
S_{cu} : copper sheet cross-sectional area
r_{ct} : contact resistivity per unit length

$$V_{all} = V(L) = I_{op}\sqrt{r_{cu} r_{ct}}\frac{e^{\alpha L} + e^{-\alpha L}}{e^{\alpha L} - e^{-\alpha L}}$$

$$V_{cu} = \int_0^L I(x) r_{cu}\, dx = I_{op}\sqrt{r_{cu} r_{ct}}\frac{(e^{\alpha L} + e^{-\alpha L} - 2)}{e^{\alpha L} - e^{-\alpha L}}$$

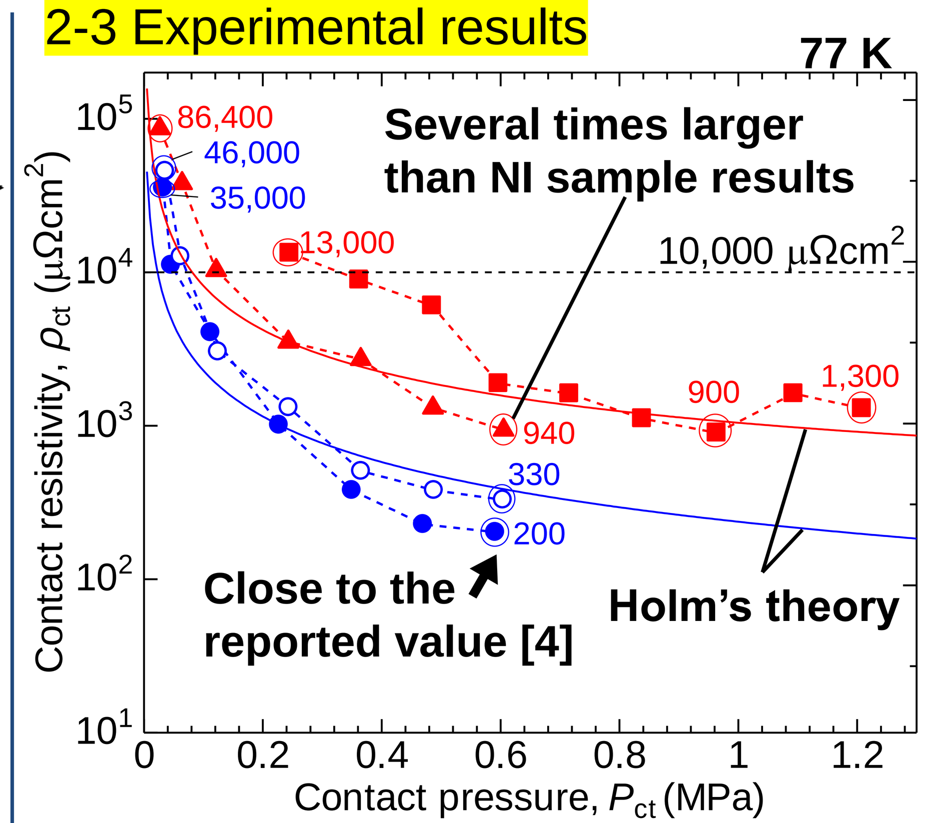
The value of ρ_{ct} is fitted by the least squares method

$V_{all\_exp} \Rightarrow V_{all\_analysis}$
$V_{cu\_exp} \Rightarrow V_{cu\_analysis}$

[3] Wilson, "Superconducting Magnets" (1983)

ρ_{ct} : contact resistivity
w : contact width
I_{op} : supply current
L : contact length

2-3 Experimental results



Holm's electrical contact theory[5][6]

Resistance due to asperity spots $R_{ct} \propto 1/P_{ct}$

Resistance due to surface contaminations $R_{ct} \propto 1/P_{ct}$

$y = \frac{18}{\sqrt{x}} + \frac{786}{x} + 242$

$y = \frac{7}{\sqrt{x}} + \frac{226}{x} + 4$

[4] X Wang et al. SUST 26(2013) 035012
[5] J Lu et al. SUST. 30(2017) 045005
[6] R Holm. "Electric Contacts Theory and Application Fourth edition" Springer (1976)

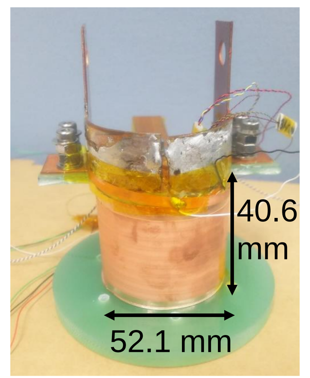
Short summary

- We successfully obtained the contact resistivity ρ_{ct} - contact pressure P_{ct} curve for the LNI contact model, which follows the well-known Holm's electrical contact theory.
- The value of ρ_{ct} for the LNI contact model was several times higher than that for the NI contact model.

3. Coil experiment

3-1. Experimental setup

	Unit	LNI-REBCO coils (Winding tension F = 2, 4, 6 kgf)
REBCO conductor	-	SuperPower SCS4050
Conductor Width/Thickness	mm	4.03 / 0.097
Conductor critical current at 77 K	A	181
Inner diameter	Mm	50.08
Outer diameter	mm	52.1 (F = 2 kgf) / 52.3 (F = 4 kgf) / 52.2 (F = 6 kgf)
Coil height	mm	40.6
Number of turns	-	80 (10 turns × 8 layers)
Coil constant	mT A⁻¹	1.54
Calculated coil critical current at 77 K	A	86.02
Self-inductance	mH	0.25



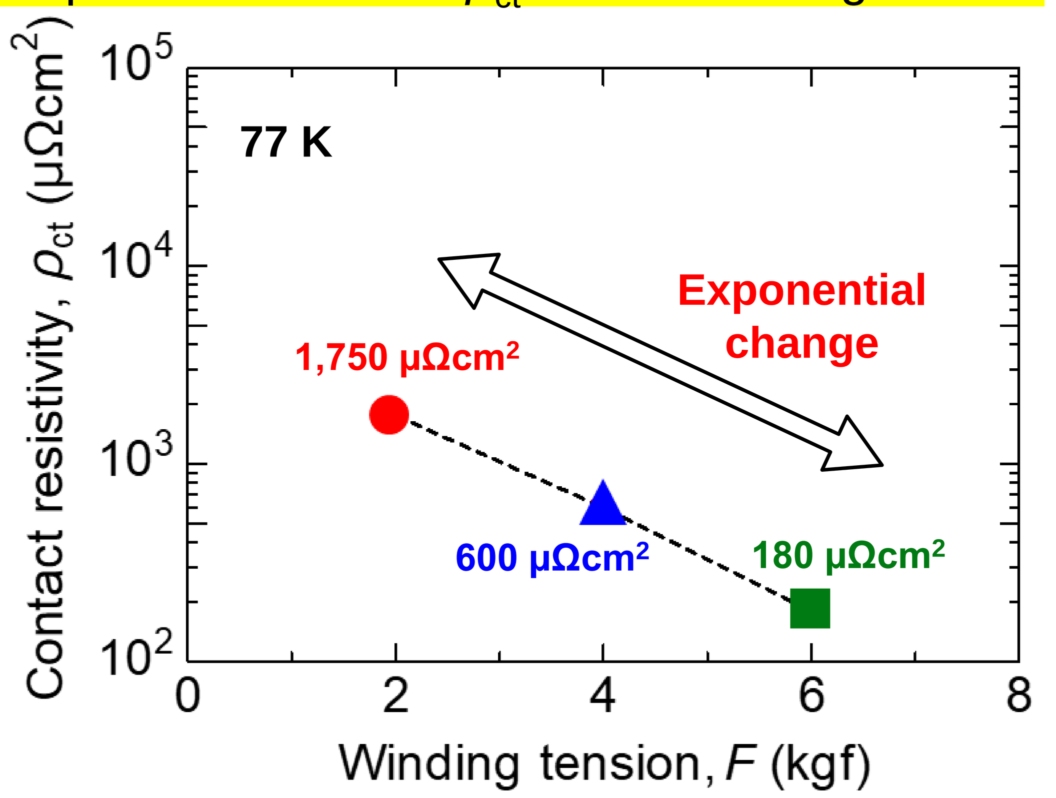
LNI-REBCO coil (Winding tension F = 2 kgf)

Inter-layer sheet

Method to estimate the value of ρ_{ct}

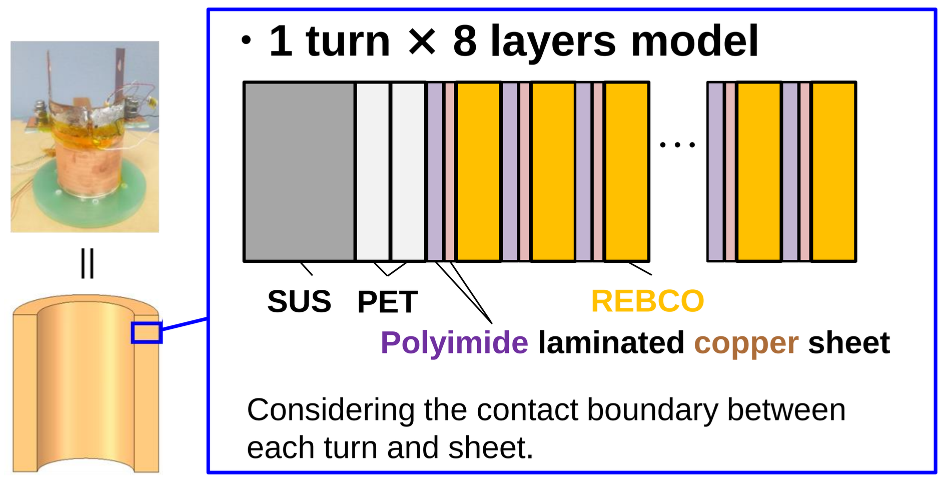
1. Power supply shut down test at 77 K to obtain a center field decay curve.
2. Fitting the value of ρ_{ct} by using an equivalent circuit model for the LNI coil [1].

3-2. Experimental result: ρ_{ct} versus winding tension



- The value of ρ_{ct} exponentially decreases with F, which is clearly different from the dependence obtained for the contact model (2-3) as well as the behavior predicted by the Holm's electrical contact theory.
- The result implies that ρ_{ct} is neither dominated by asperity spot nor surface contamination but another mechanism.
- Thus, we conducted structural analysis considering winding tension and thermal contraction.

3-3. Discussion : Structural analysis for contact condition, considering winding tension and thermal contraction during cooling

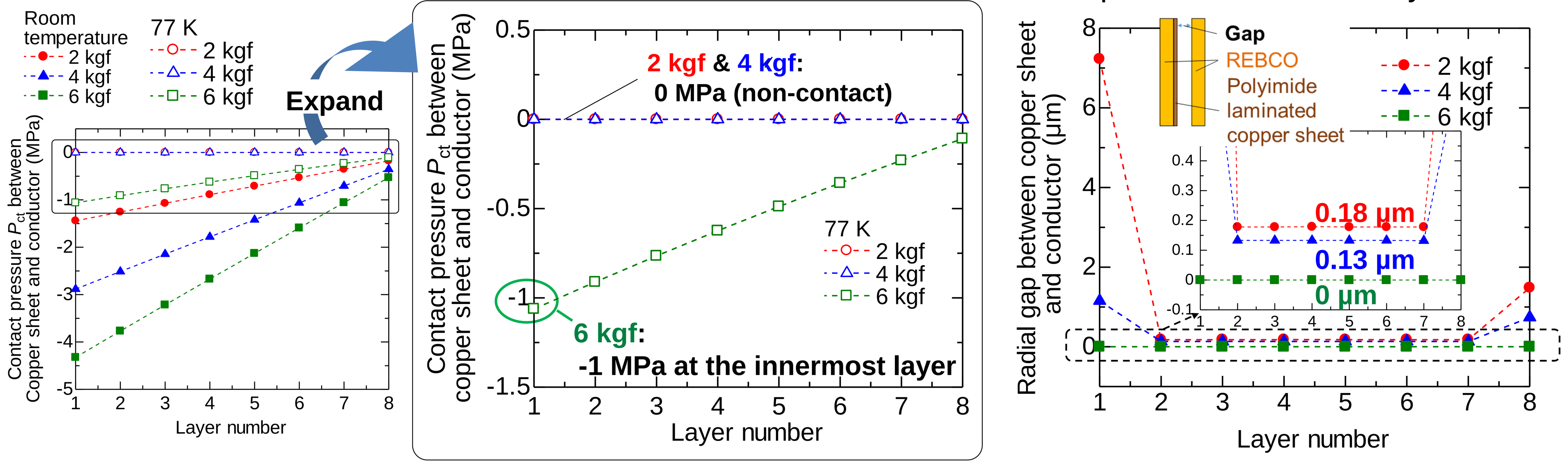


	Young's modulus (GPa)	Poisson's ratio	Thermal Expansion (%)
REBCO conductor	Considered by an elastic matrix described in ref. [7]		r : 0.426[8] θ : 0.235[8]
Polyimide	3.1[11]	0.3[11]	0.42[9]
Copper	98[7]	0.34[7]	0.31[9]
PET	1[10]	0.21[10]	0.42[9]
SUS	193[11]	0.3[11]	0.295[9]

[7] Y Yang et al. J. Appl. Phys., vol. 124, no. 7, Art. no. 073902, 2018.
[8] H Miyazaki et al. IEEE. 25(2015) 6602305
[9] J. W. Ekin :, Oxford University Press, pp. 234-234.
[10] DJK Corporation web page [11] X Wang et al, IEEE. 26(2016) 4600804

Analysis results

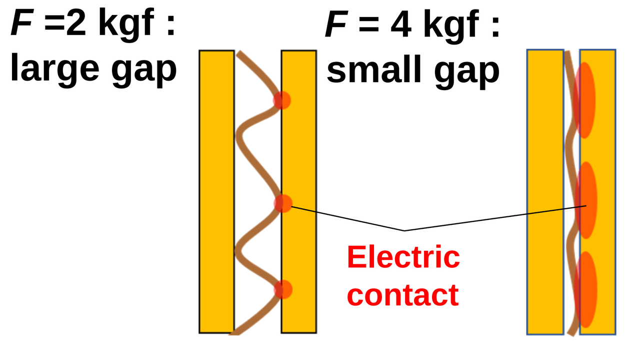
☐Contact pressure between layers ☐ Gap distance between layers



- **Due to thermal contraction during cooling (especially the polyimide sheet), ρ_{ct} is not proportional to the F.**
- **In the cases of F = 2 kgf and 4 kgf, there are no contact between REBCO conductor and copper sheet.**
- **Winding pack becomes loose due to thermal contract, which is one of the drawbacks of the LNI method.**

Why does the experimental result show a finite contact resistance even though the simulation indicates there is no inter-layer contact?

Possible explanation



The gap is formed due to cooling.
⇩
The sheets can be deformed inside the gap.
⇩
Local contacts between sheets and conductors are generated.

Contact model test results vs coil test results

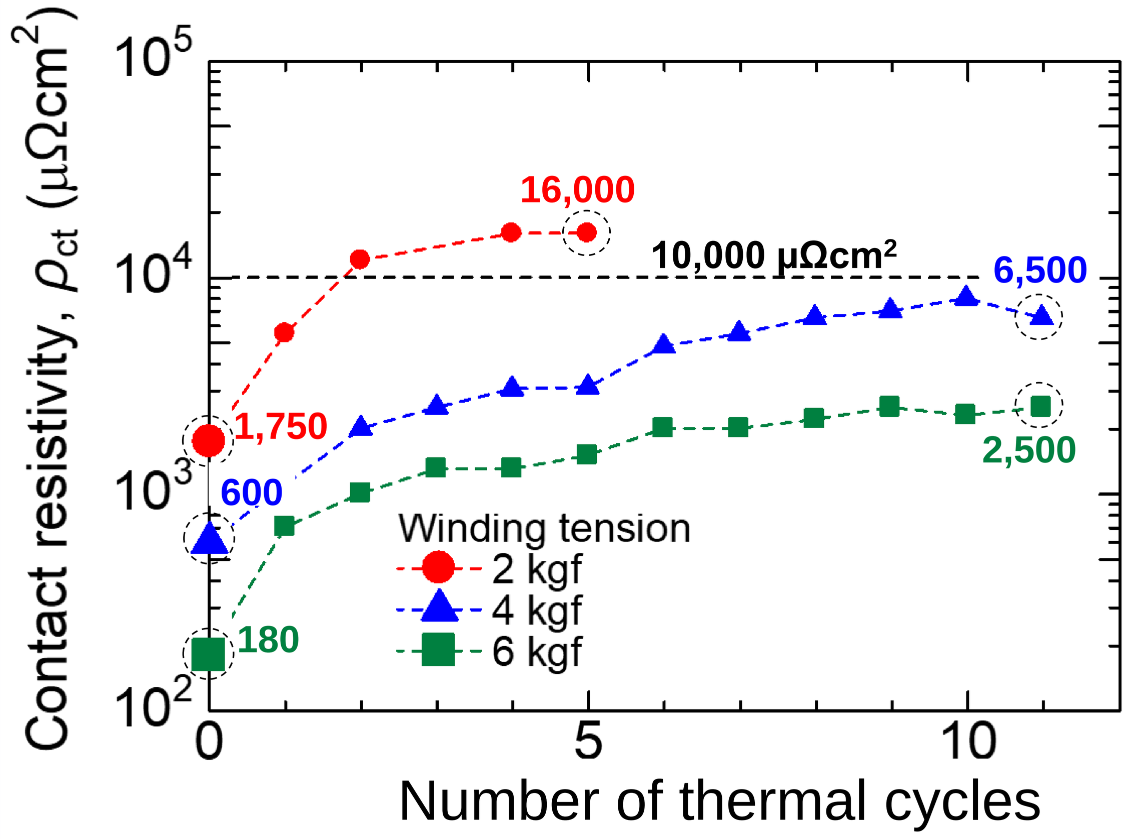
Contact sample result	**Coil sample result**
When P_{ct} = ~ 1 MPa,	When P_{ct} = ~ 1 MPa (from structure analysis result of F = 6 kgf),
ρ_{ct} = 900 μΩcm²	⇦ ×5 **ρ_{ct} = 180 μΩcm²**

Why? The reason is unclear.

The gap between the conductor and copper sheet may make it difficult to control the contact resistivity.

3-4. Experimental result: Effects of thermal cycles on the value of ρ_{ct}

We repeatedly conducted power supply shut down test and thermal cycle. (Room temperature ⇔ 77 K)



For each winding tension, the value of ρ_{ct} increases with thermal cycles and saturate at a value ~10 times higher than the initial value.

Possible explanation

1. Thermal contraction during cooling makes the inter-layer sheets deformed.
2. The sheets are deformed again through warming up, but do not return to the previous state.
3. Cooling again makes the sheets deformed further.

⇩(Repeating thermal cycles with 1-3.)

4. Deformation of the sheets saturates.

Short summary

- In the LNI-REBCO coil, the contact resistivity ρ_{ct} exponentially decreased with increasing winding tension in the range from 2 kgf to 6 kgf.
- According to structural analysis, inter-layer gaps are formed due to thermal contraction in the case of a low winding tension. It might affect the ρ_{ct} value.
- The exponential relationship between ρ_{ct} and the contact pressure P_{ct} did not correspond to the inverse proportional relationship obtained for the contact model experiment.
- As the coil experienced thermal cycles, ρ_{ct} increased and saturated at a value ~10 times higher than the virgin value.

Conclusions

- The present study revealed that a high ρ_{ct} value, such as >10,000 μΩcm², can be obtained under a low winding tension after numbers of thermal cycles.
- As the present study also showed, however, it is difficult to strictly control the value of ρ_{ct} for a dry-winding LNI-REBCO coil in practical since it substantially depends on the contact condition, which might be dominated by a winding tension and thermal cycles as well as charging/discharging and quenches.
- For controlling the value of ρ_{ct}, wet-winding might be a solution to "freeze" the contact condition even under various external effects. We will make investigations on this approach based on a previous work for wet-winding LNI-REBCO coil [12].

[12] Yoshida et al., IEEE TAS, 31, 5 (2021)