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Contact resistivity between REBCO tapes coated with a thin resistive layer

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MT25

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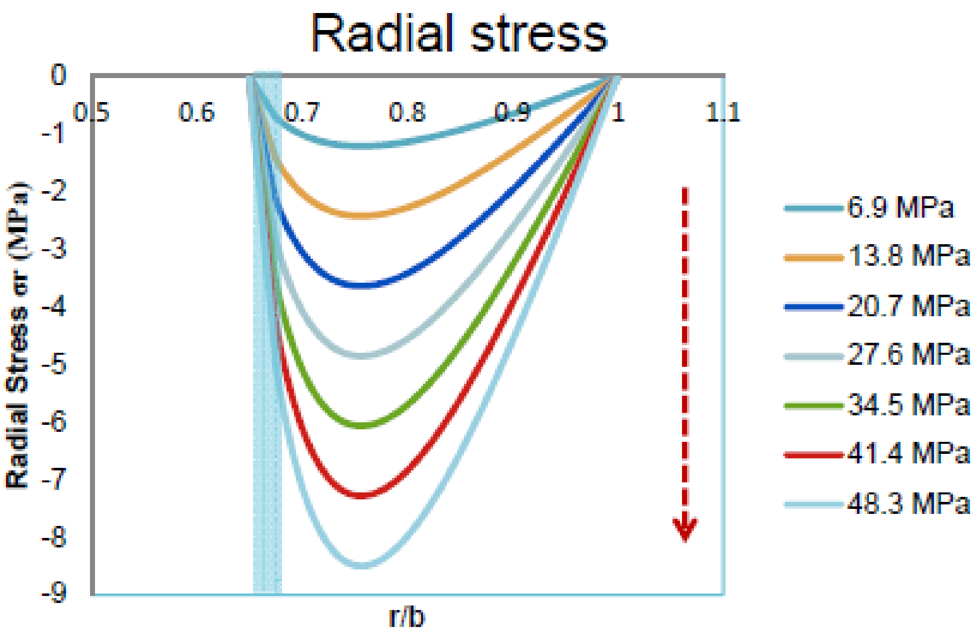
Introduction

- Turn-to-turn contact resistivity (Rc) is a key parameter for NI REBCO coil. It relates to self-protection ability, charging delay and ramp losses.
- Appropriate range of Rc, 10^2 -10^4 $\mu\Omega$-cm^2 (W.D. Markiewicz and S. Noguchi)
- Reliable Rc measurement has been performed at the NHMFL (ASC 2016 and SUST 2017).
- Applying various surface coatings is one way to control Rc. Effects of different coatings and the load cycles will be presented.

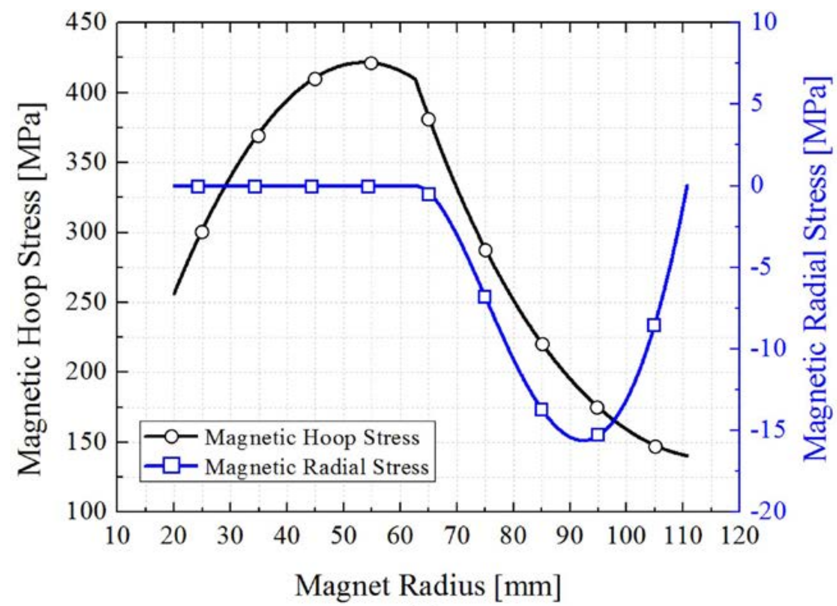
Contact pressure in REBCO DP coil

Contact pressure = Winding + Thermal + Electromagnetic

Winding tension



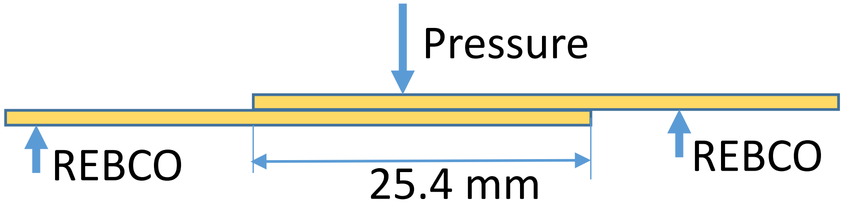
Electromagnetic

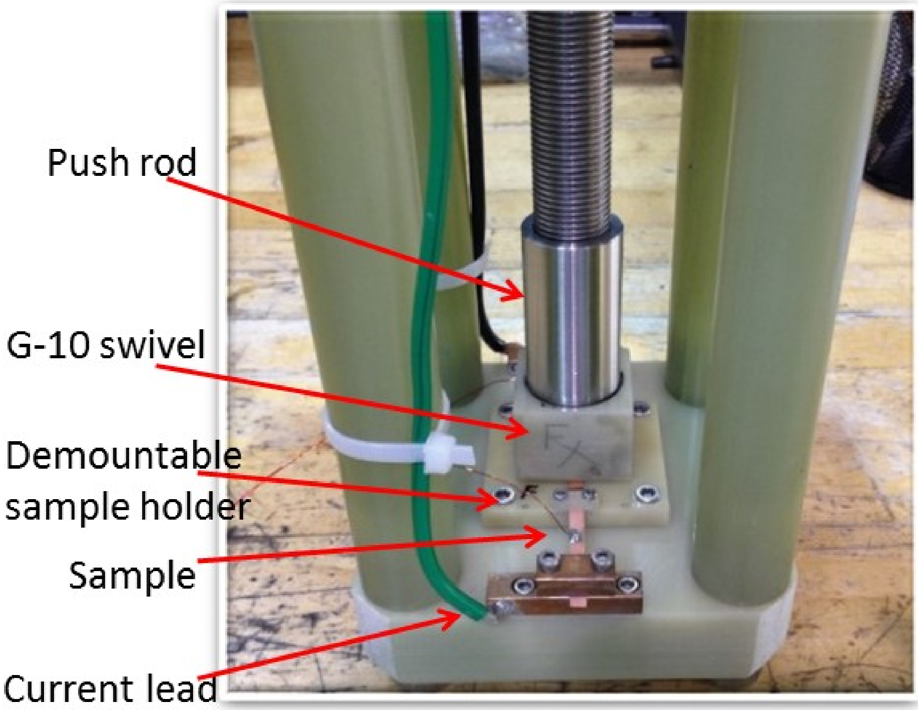


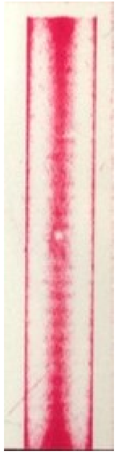
H. Song, et al, IEEE trans. Appl. Supercond., 4601305. 2017

K. Kim, et al., Supercond. Sci. Technol, 065008, 2017

Rc Experimental Setup I







Fuji film
20 MPa
SuperPower
SCS4050

- Load is controlled by air pressure and calibrated with a load cell. Max pressure = 150 MPa.
- Alignment checked by a Fuji film.

Rc vs large number of load cycles at 77 and 4.2 K

- Load cycle between 2.5 and 25 MPa, up to 10 Hz frequency.
- Resistance is measured by injecting + / – 1 A current.

R_c variation in uninsulated conductors (no load cycle)

No.	Sample	Surface	# of samples	Rc 1st load at 25 MPa ($\mu\Omega$-cm^2)
1	SuperPower	As-received, no cleaning	3	45-2000
2	SuperPower	Ethanol wiped	13	16-58
3	SuperPower	Finger handled	1	100
4	SuperPower	Scotch-brite wiped	5	0.8-7.3
5	SuperPower	HCl etched	6	3.4-22
6	SuperPower	Ethanol wiped End of a spool	7	47-180
7	SuNam	Ethanol wiped	2	5.9-7.5

There is two orders of magnitude variations in Rc, depending on surface conditions.

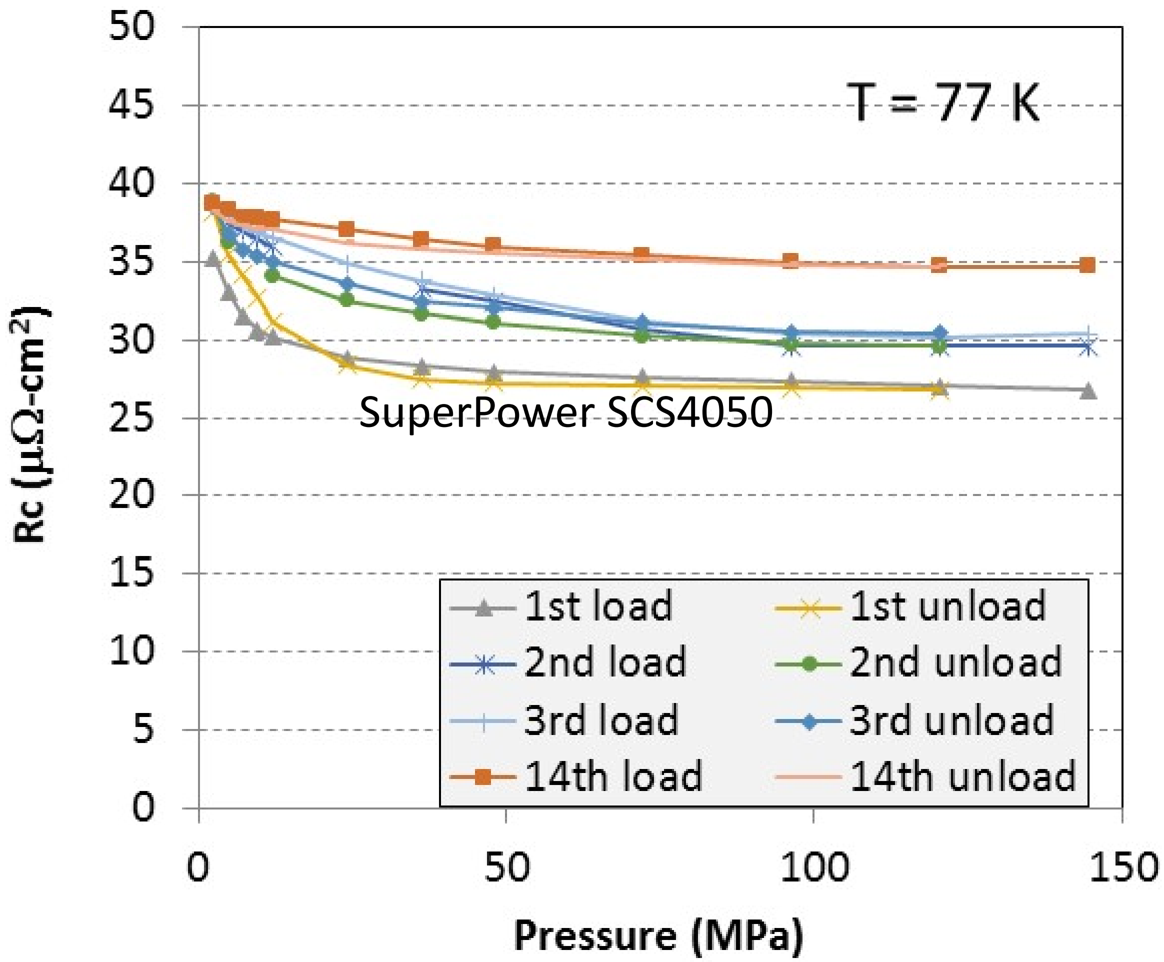
Rc after surface coating (no load cycle)

No.	Sample	Surface	# of samples	Rc at 24 MPa ($\mu\Omega$-cm^2)
1	SuperPower	Ni plating	5	19-580
2	SuperPower	Cr plating	3	75-1000
3	SuperPower	A stainless steel tape in between	3	28000-33000
4	SuNam	Stainless steel plating	2	180,224
5	SuperPower	Ebonol oxidized at RT	3	6-960
6	SuperPower	Graphite sprayed	1	180

- Rc has large variations.
- Rc of stainless steel coated seems to be more consistent.

Effect of low number of load cycles (ASC-2016)

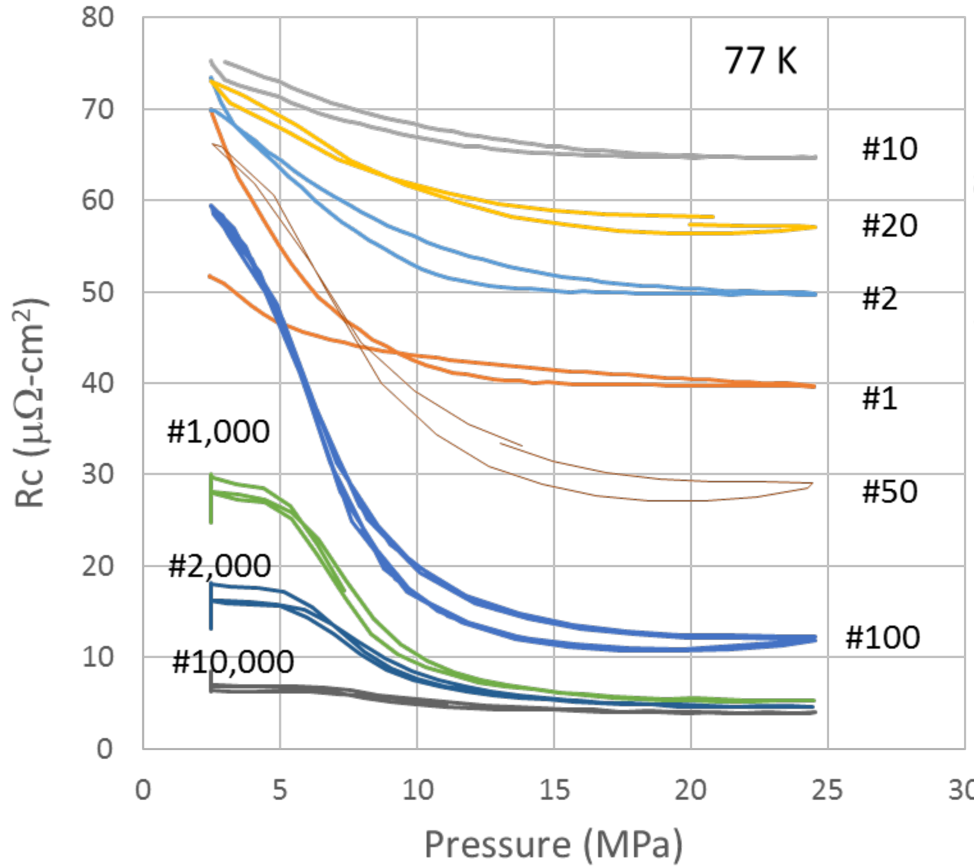
SuperPower SCS4050

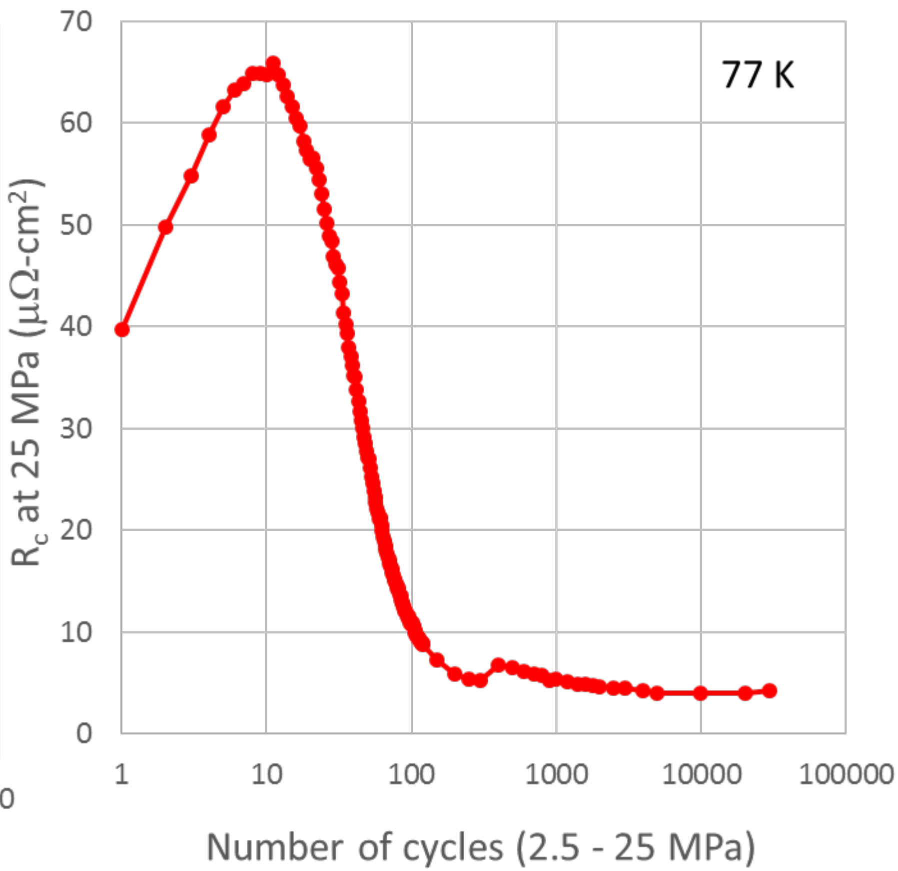


Rc inceases with load cycle. Cold-work effect?

Effect of large number of load cycles:

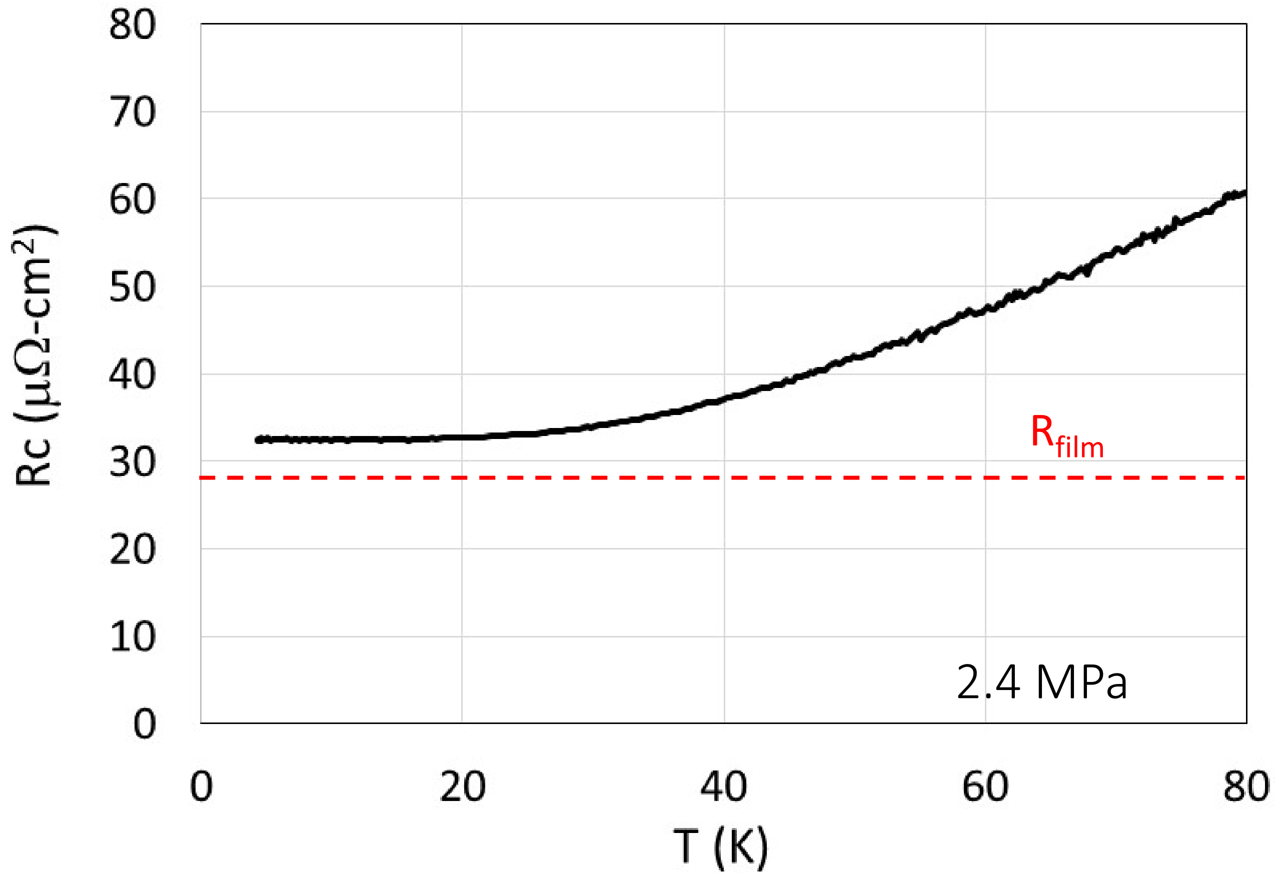
SuperPower SCS4050





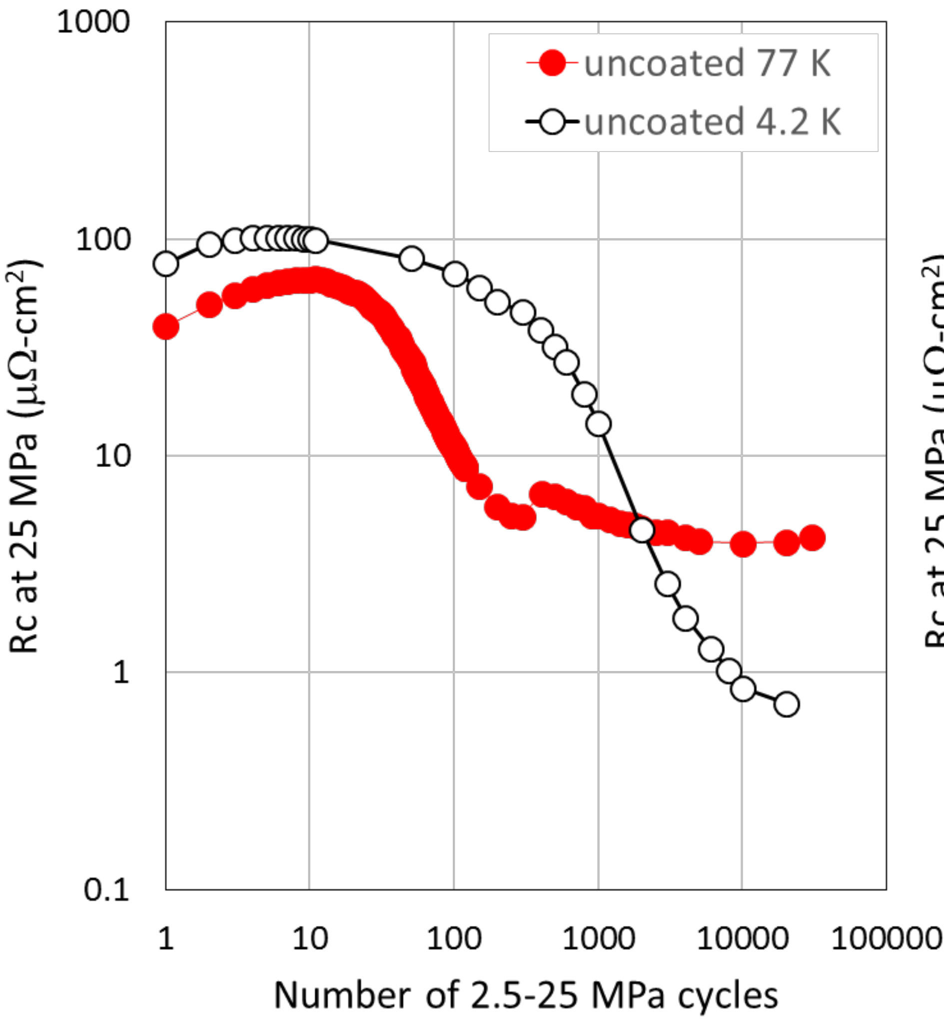
At the end of 10,000 cycles, Rc ~ 5 $\mu\Omega$-cm^2. one order of magnitude smaller Rc.

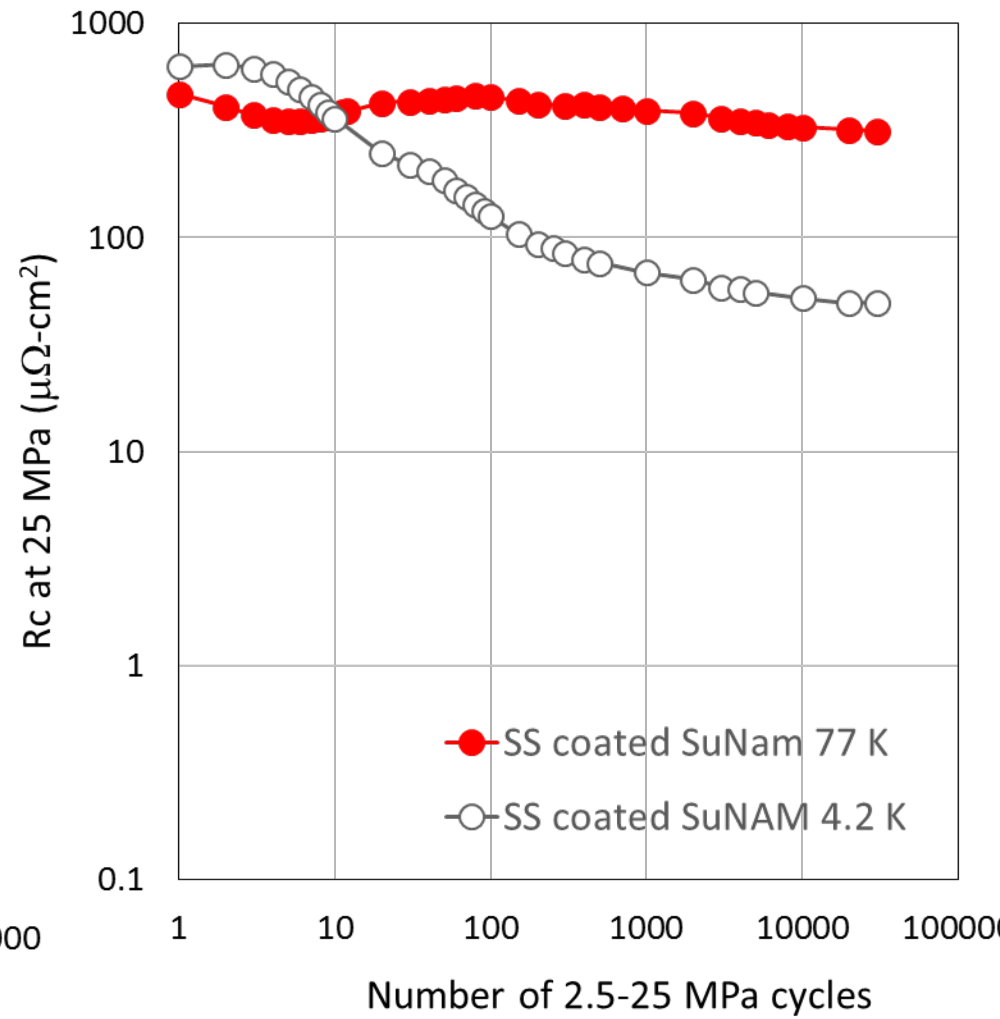
Rc temperature dependence (ASC-2016)



- Rc increases with T, similar to behavior of copper $\rho(T)$, consistent with constriction resistance.
- The low resistivity ratio can be explained by a T independent R_{film}.

Rc at 77 K versus 4.2 K





At the end of 10,000 cycles, 4.2 K Rc is a few times smaller than at 77 K.

Control of Rc: thin film coating

- Stainless steel coating seems to work well. But a wider range of control over Rc is desirable.
- We are searching for economical methods that can customize Rc to a wide range of values.

TWO APPROACHES

A: thin film coating on REBCO tape to increase Rc

- Pro: Eliminate the co-winding process, higher Jw
- Con: process risking REBCO
- Tested
  1. Cr plating
  2. Ni plating
  3. Ni-P plating
  4. Cu oxidation by Ebonol® C

B: thin film coating on stainless steel tape to decrease Rc.

- Pro: no risk on REBCO, low R&D cost.
- Con: Co-winding, low Jw.
- Tested:
  1. Cu plating
  2. Ni plating

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Electroless Ni-P plating

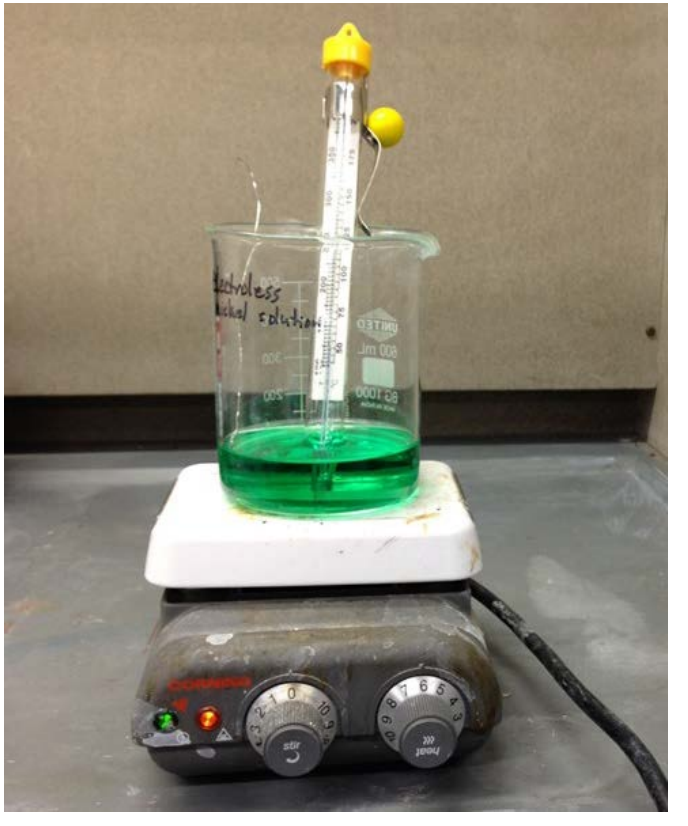
- Ni-P electroless plated material has up to 10% P and high resistivity.
- Commercial solution (Caswell Inc. US) consists of nickel sulfate ($NiSO_4$) and sodium hypophosphite (NaH_2PO_2) and hydroxyl complex acid and organic matter with carboxylic group are added to control the chemical reaction:

$$Ni^{2+} + H_2PO_2^{-} + H_2O \xrightarrow{Ni} Ni^{0} + H_2PO_3^{-} + 2H^{+}$$

$$H_2PO_2 + H_2O \xrightarrow{Ni} H_2\uparrow + H_2PO_3^{-}$$

REBCO immersed in solution at 90 C for 10 min.
5 μm layer thickness (as measured by weight gain)

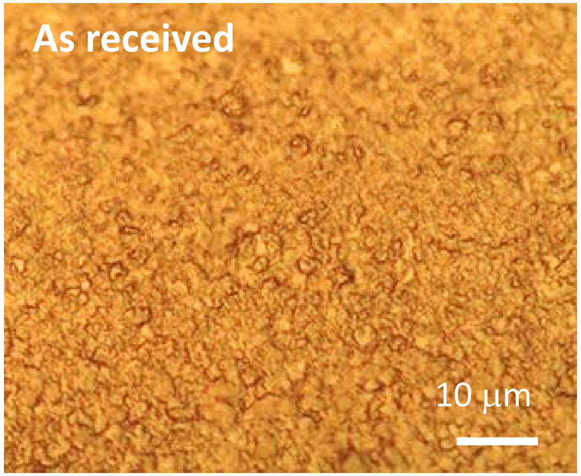
Coating thickness (μm)	Rc at 150 MPa (μΩ-cm²)
5	1524
2	1292

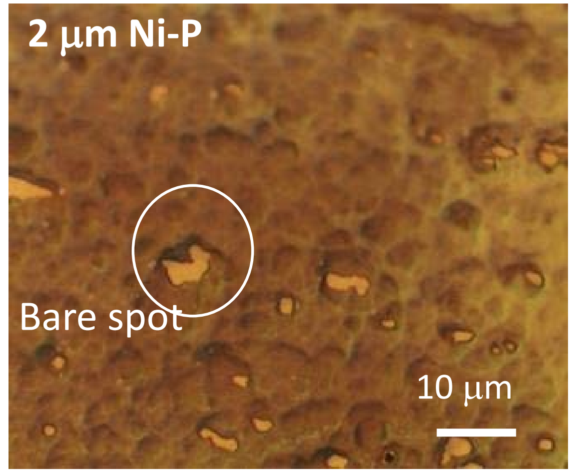


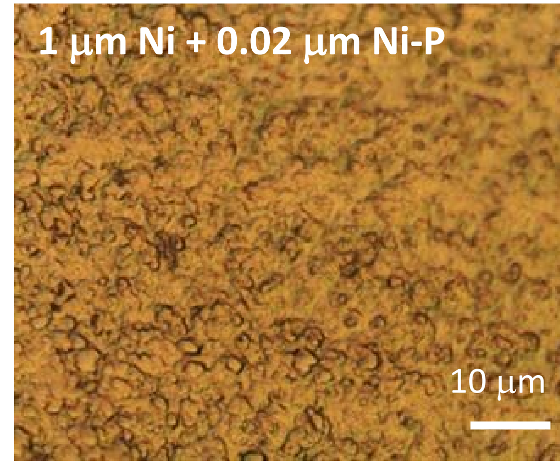
Solder splice of Ni-P plated samples has resistivity 1 μΩ-cm².

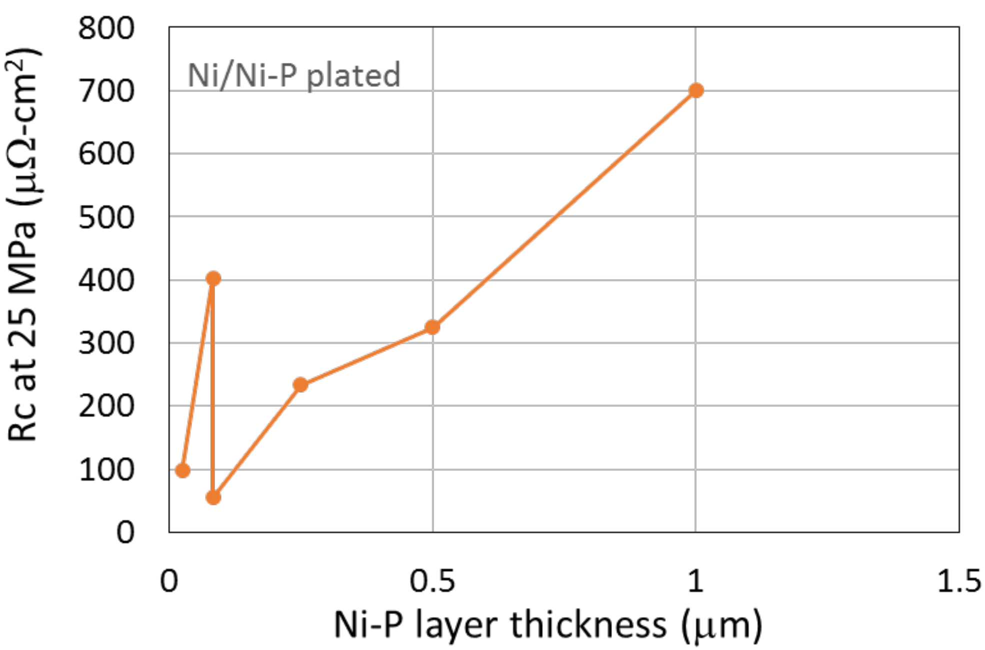
Ni-P/Ni plating

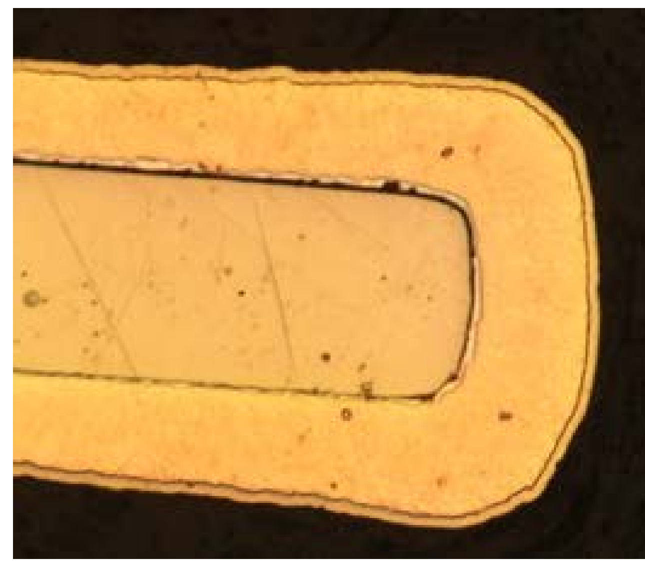
For better uniformity, 1 μm Ni layer is electroplated before Ni-P plating



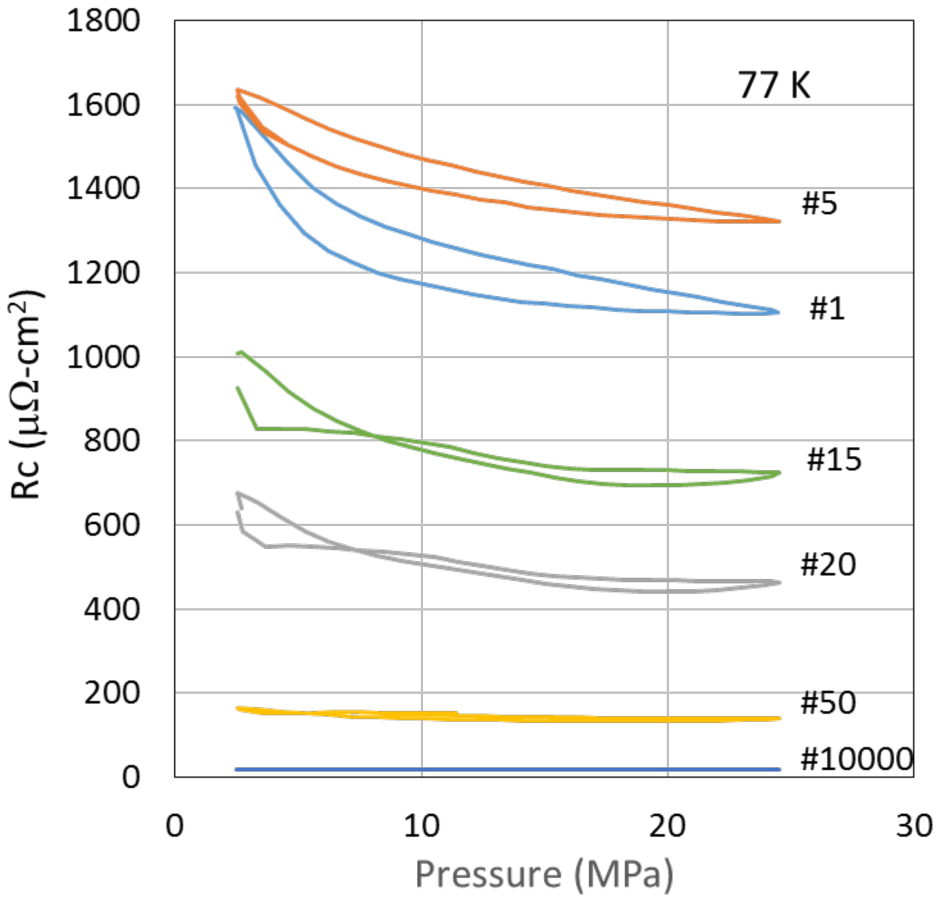


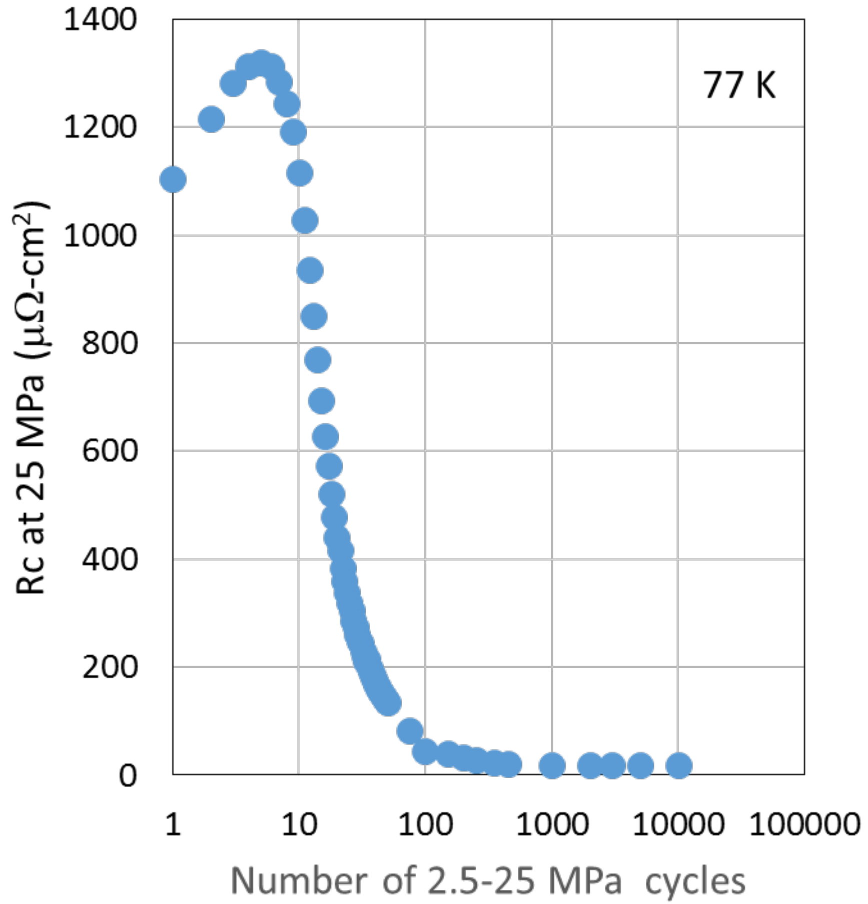






0.8 μm Ni-P/1 μm Ni plated SCS4050

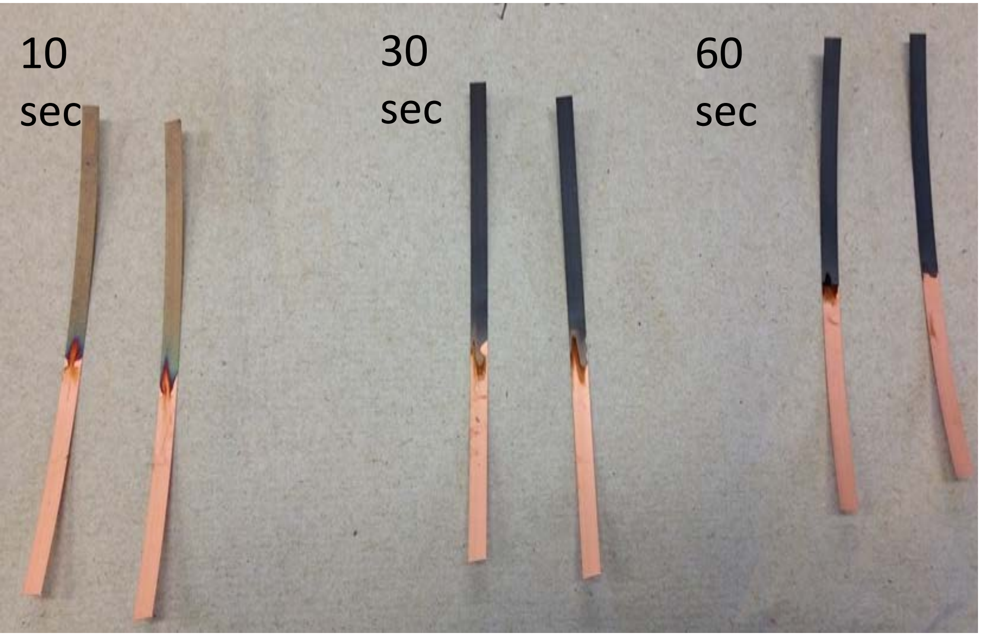


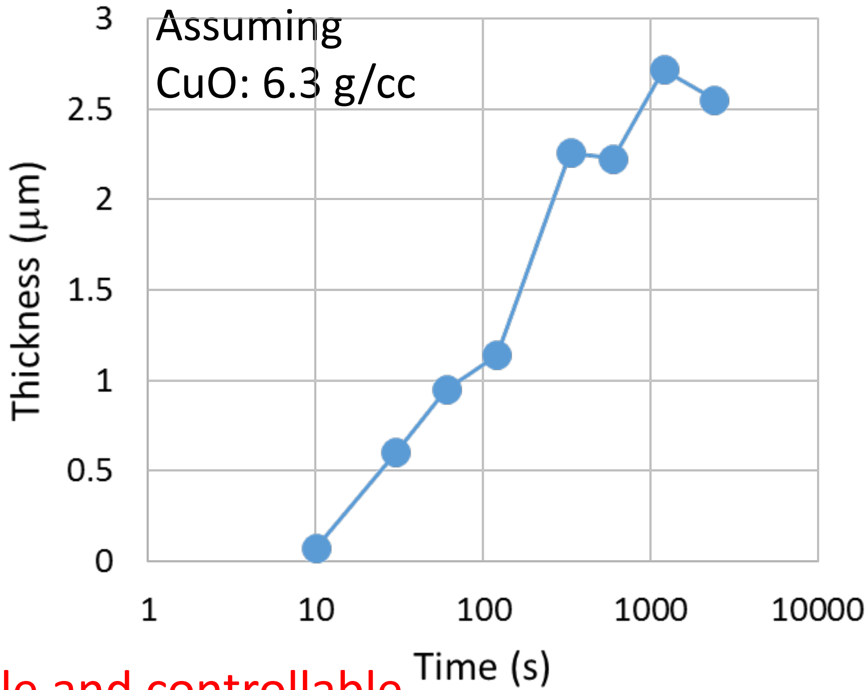


At the end of 10,000 cycles, Rc ~ 18 $\mu\Omega\text{-cm}^2$

Ebonol® C oxidation

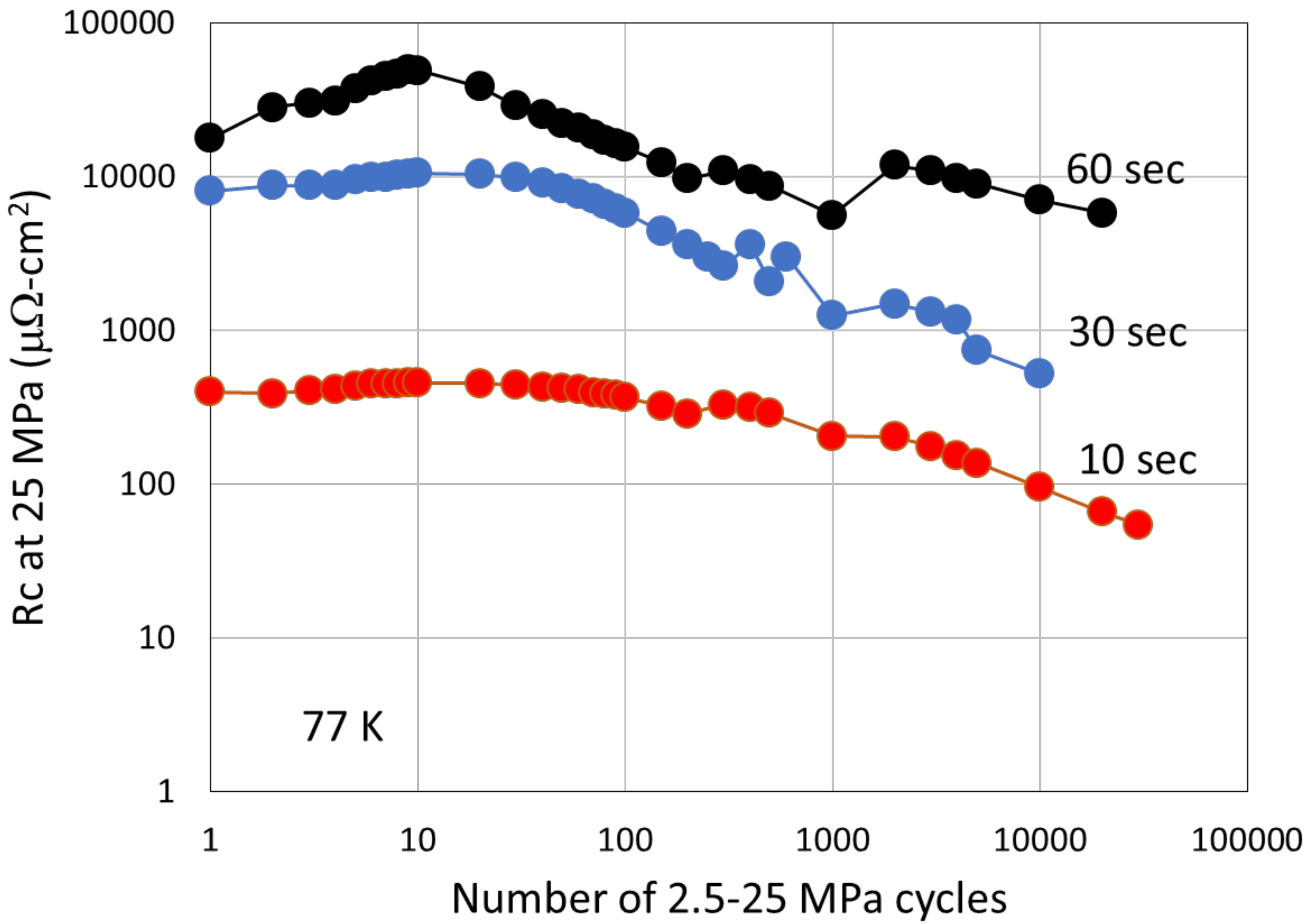
Ebonol C powder:	$NaOH : NaClO_2 = 2:1$
Concentration:	Ebonol: H_2O = 18:80
Surface treatment:	HCl: H_2O = 1:10
Oxidation temperature:	98 °C





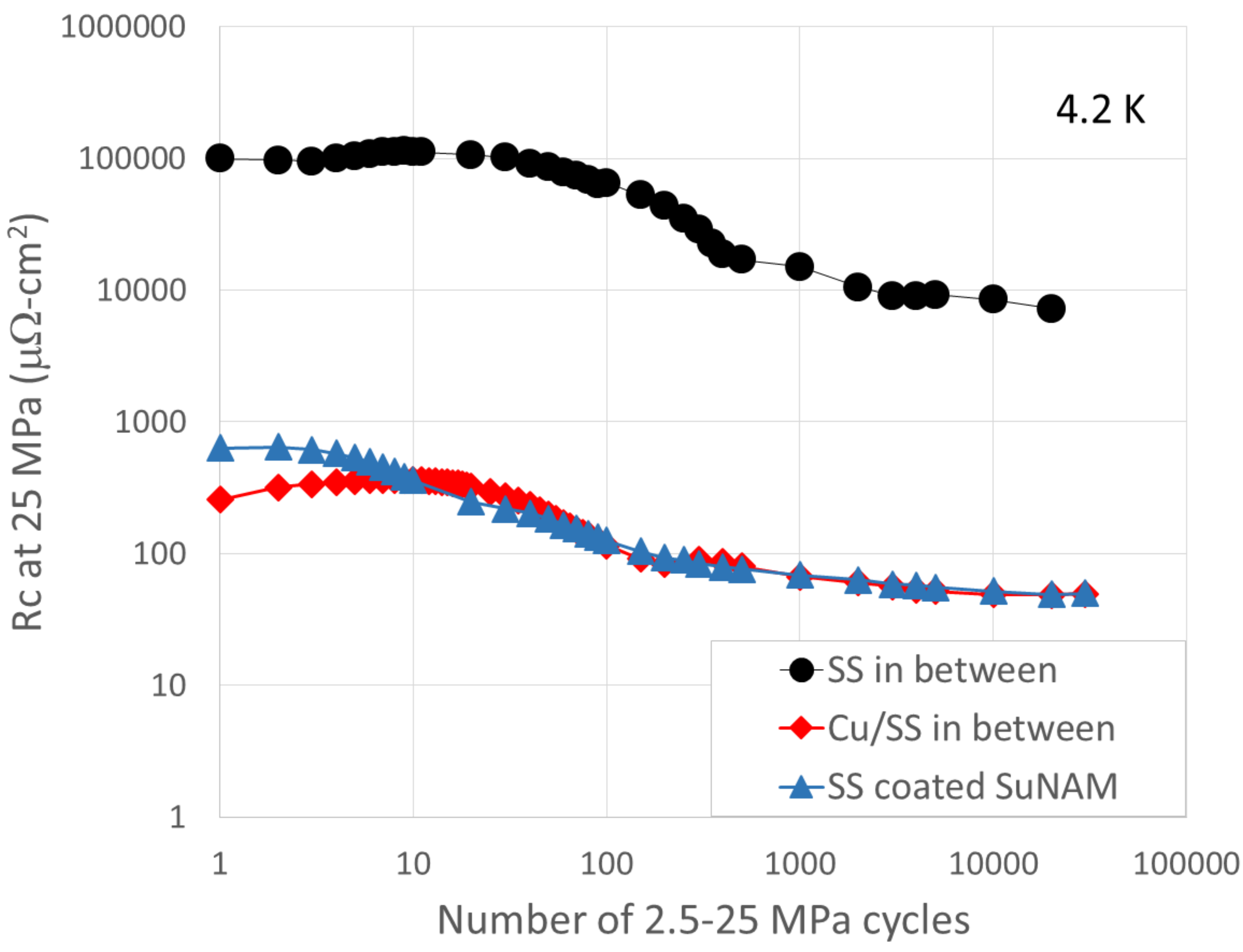
The process is low cost, reliable and controllable

Rc of ebonol oxidized samples



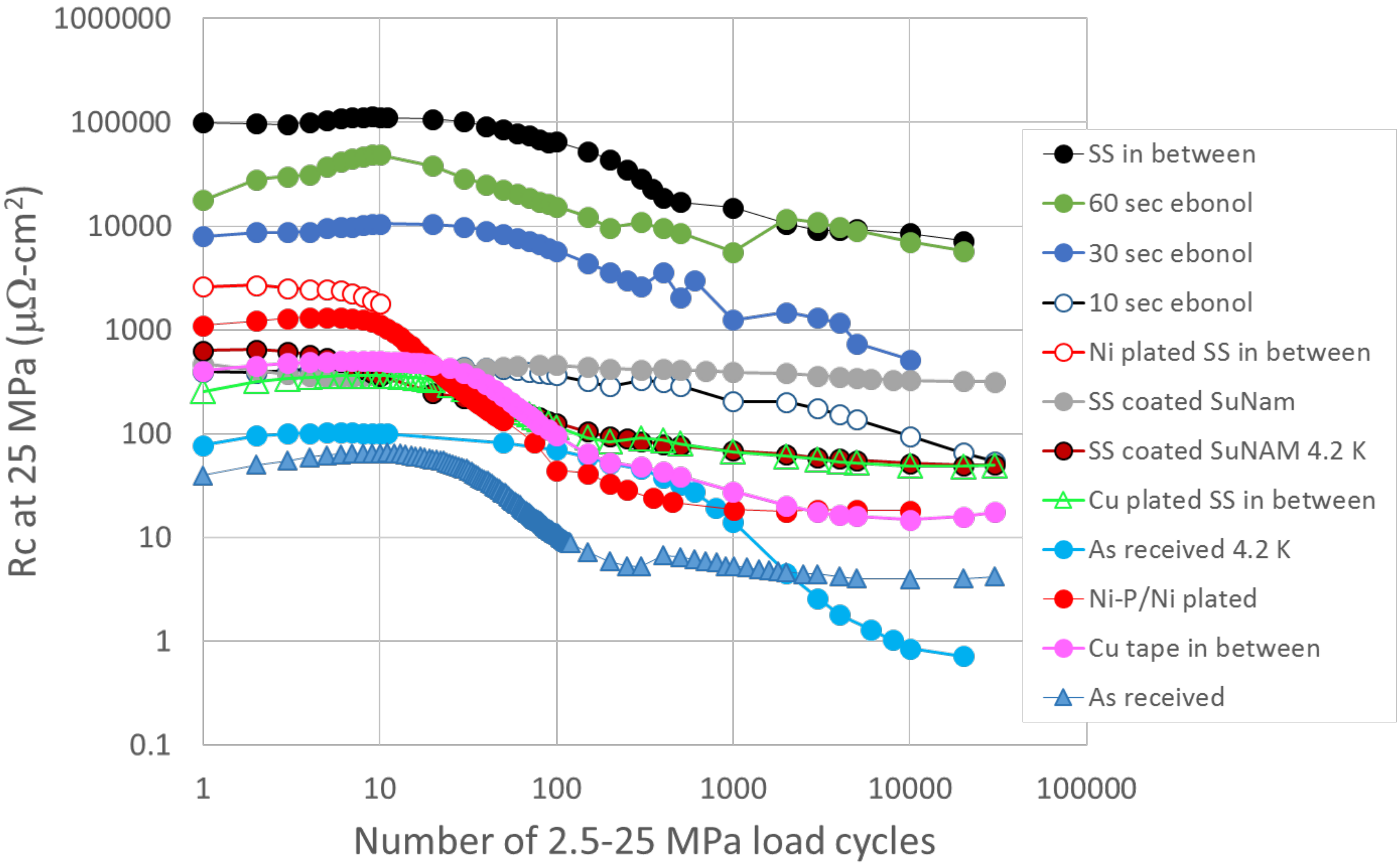
Rc increases with oxidation time, moderately decreases with load cycles

50 μm thick SS tape in between



Myung-Hwan Sohn, et al., Mon-Po 1.03-07 shows similar trend

Wide range of contact resistivity



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Summary

- Rc has considerable variations.
- Load cycling can significantly reduce Rc.
- Rc is lower at 4.2 K than at 77 K.
- Rc can be controlled in a wide range by either
    1. oxidation of copper, or
    2. electroplating of stainless co-winding tape.

Acknowledgement

We thank Prof. Seungyong Hahn and his team for helpful discussions and for providing SS coated conductor samples. Dr. Chris Rey for providing Ebonol® C.

THANK YOU!