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Mechanical Properties of $BaHfO_3$-doped EuBCO Coated Conductors Fabricated by Hot-wall PLD on IBAD Template

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Introduction

- **$REBa_2Cu_3O_x$ (REBCO) coated conductors (CCs) are optimal for high-field magnet applications because of:**
  - High in-field critical current (I_c) performance,
  - High tensile stress tolerance.

- **In order to further enhance the in-field I_c, we have developed practical $BaHfO_3$ (BHO)-doped EuBCO CCs using hot-wall PLD.**
  - Long length over 600 m & excellent I_c homogeneity,
  - High I_c properties under high fields & low temperatures.

S. Fujita, *et al*., IEEE Trans. Appl. Supercond., vol. 28, no. 4, 6600604 (2018).
S. Fujita, *et al*., IEEE Trans. Appl. Supercond., vol. 29, no. 5, 8001505 (2019).

- **For high field magnet applications, mechanical properties are important as well as I_c properties, because of enormous electromagnetic force.**

In this work

We investigated the detailed mechanical properties for following REBCO CCs fabricated by hot-wall PLD.
- **Conventional mass-production pure GdBCO CCs.**
- **New mass-production BHO-EuBCO CCs.**

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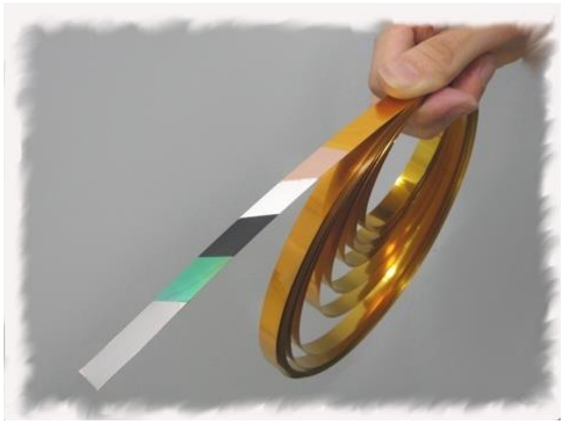
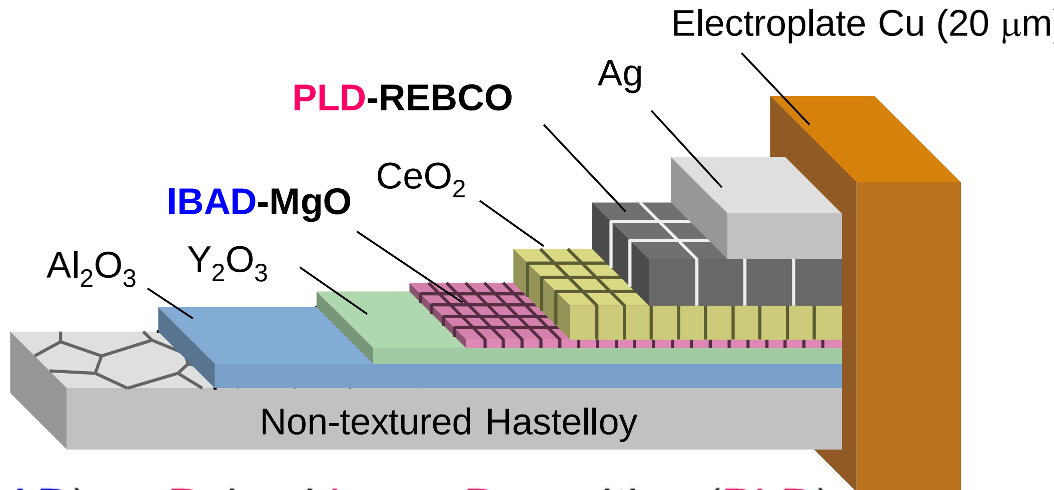
Fujikura's REBCO CC production





Ion Beam Assisted Deposition (IBAD)

R-to-R system with large ion source

Pulsed Laser Deposition (PLD)

R-to-R system with hot-wall heating

These techniques enable us to **stably** manufacture the **high-performance** and **long-length** REBCO CCs.

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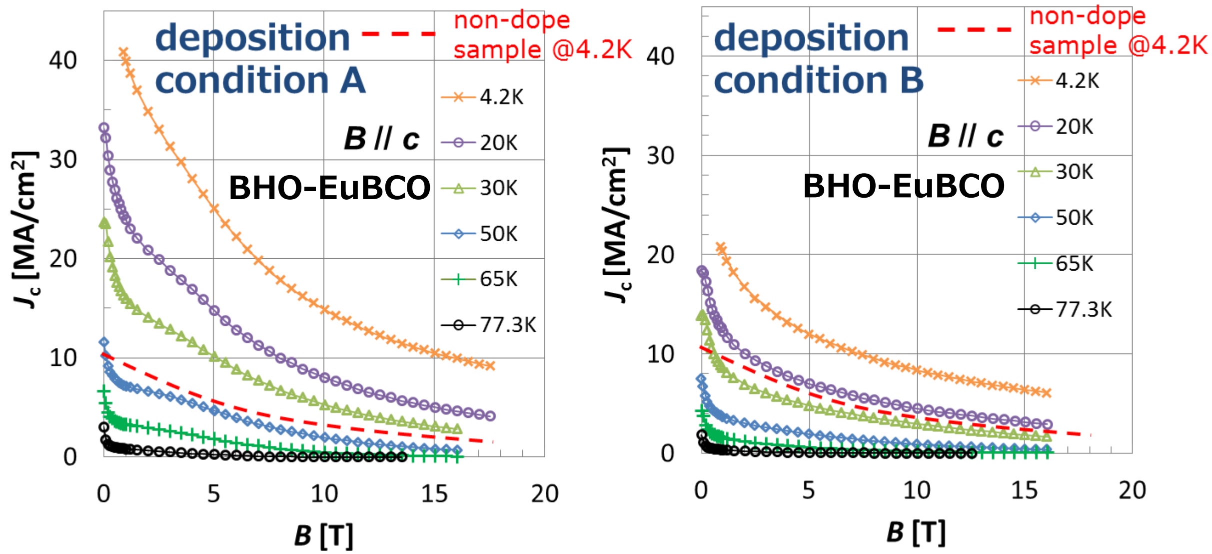
Previous works

- **Investigation of J_c property depending on REBCO deposition rate.**

Y. Iijima *et al.*, IEEE Trans. Appl. Supercond., vol. 27, no. 4, 6602804 (2017).

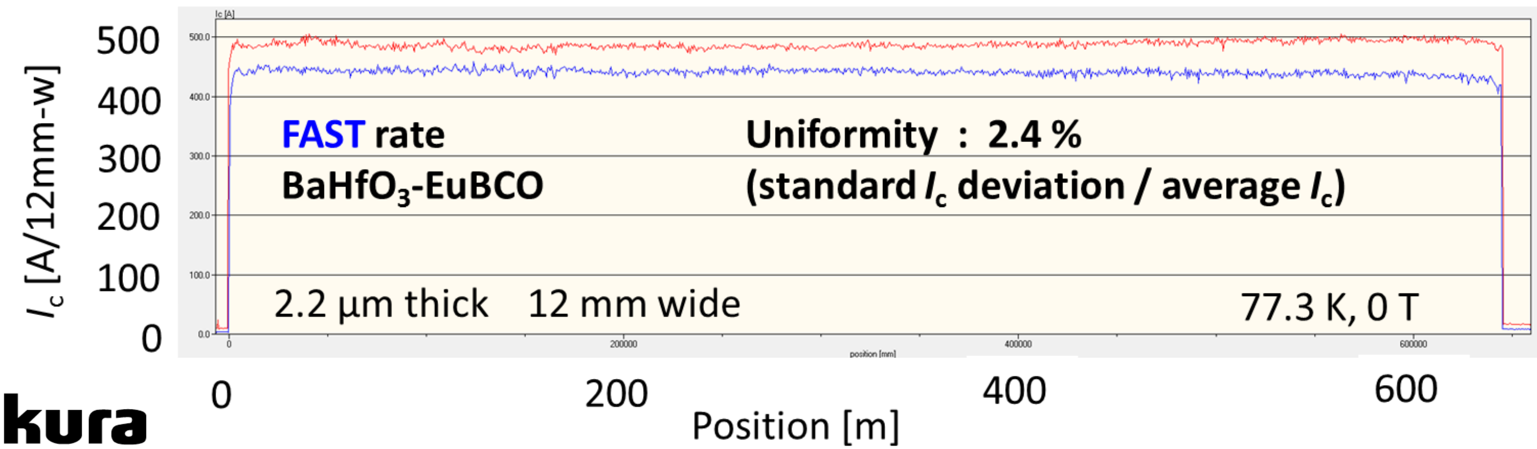
Condition A: High J_c
Growth rate ~ 5-7 nm/sec
Thickness ~ 1 μm

Condition B: High growth rate
Growth rate ~ 20-30 nm/sec
Thickness ~ 2.0-2.5 μm
→ high "I_c"



- **Fabrication of a long-length REBCO CC with good I_c uniformity.**

S. Fujita, *et al.*, IEEE Trans. Appl. Supercond., vol. 29, no. 5, 8001505 (2019).



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Evaluated REBCO CCs

Product lineup (excerpt)

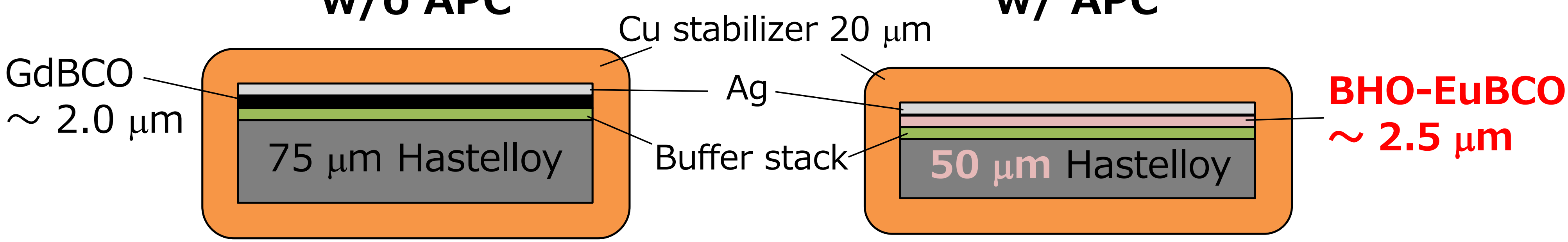
Item	REBCO layer	Width* [mm]	Thickness* [mm]	Substrate [μm]	Stabilizer [μm]	I_c@77K,s.f. [A]
FYSC-SCH04	GdBCO (Pure)	4	0.13	75	20	≧ 165
New lineup FESC-SCH04	**BHO-EuBCO**	4	0.11	**50**	20	≧ 85

E : Enhanced

* Dimensions do not include thickness of insulating tapes.

<FYSC-SCH04> w/o APC

<FESC-SCH04> w/ APC



In order to further improve the overall current density (J_e)
- **Thicker REBCO layer**
- **Thinner Hastelloy substrate**

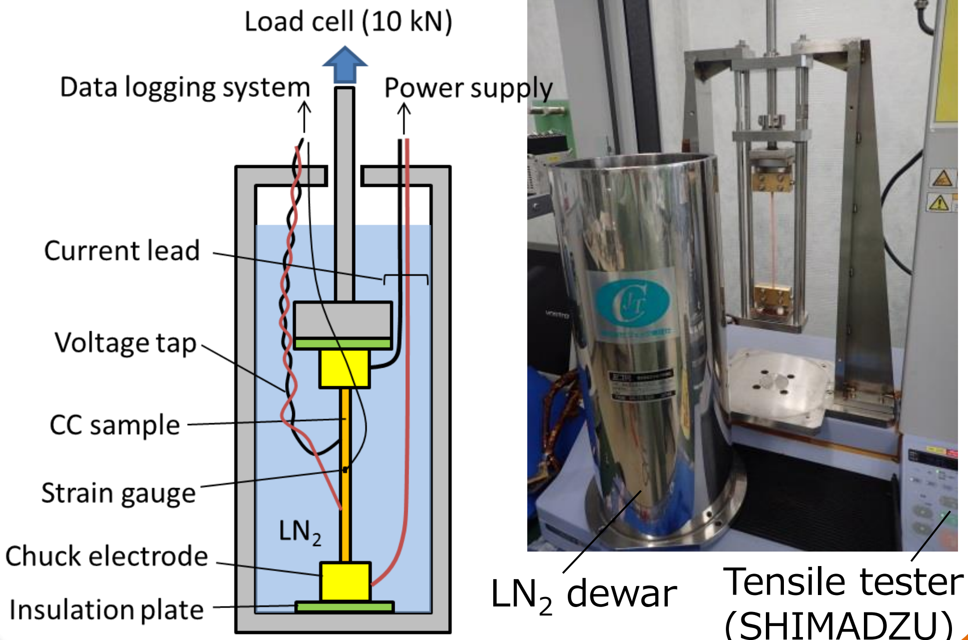
are adopted for the FESC

in field J_e : 1.8 times at 30 K

in field J_e : 2.4 times at 4.2 K

Tensile tests and bending tests

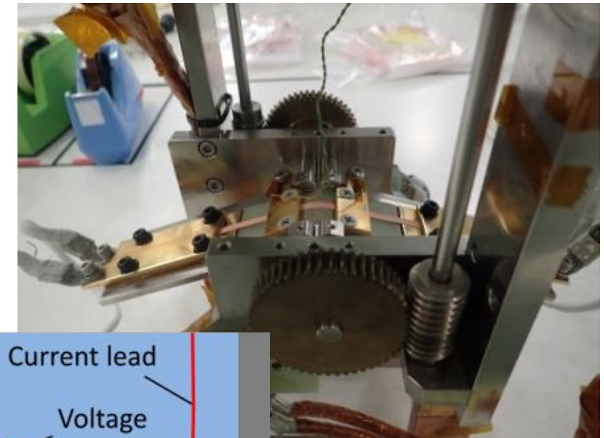
Tensile test

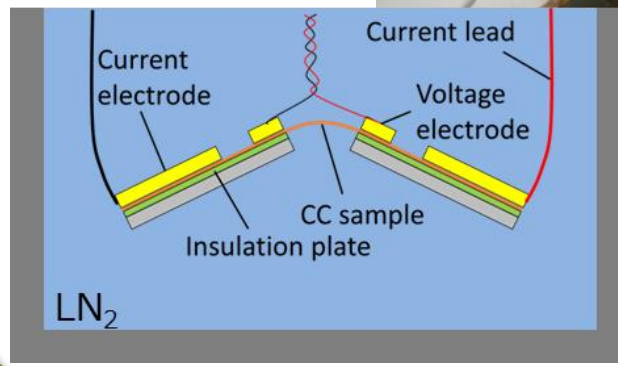


Bending test

Goldacker-type apparatus

Minimum bending radius: **5 mm**





*Manual rotation

- **Measurement procedure (in LN_2)**
  1) Measure I_c before loading ($\boldsymbol{I_{c0}}$)
  2) Load tensile or bending stress in LN_2
  3) Measure I_c during loading ($\boldsymbol{I_c^{load}}$)
  4) Measure I_c after loading ($\boldsymbol{I_c^{unload}}$) (unloading state)

Increase the load
Repeat until I_c^{unload} degrades

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Cyclic fatigue tests

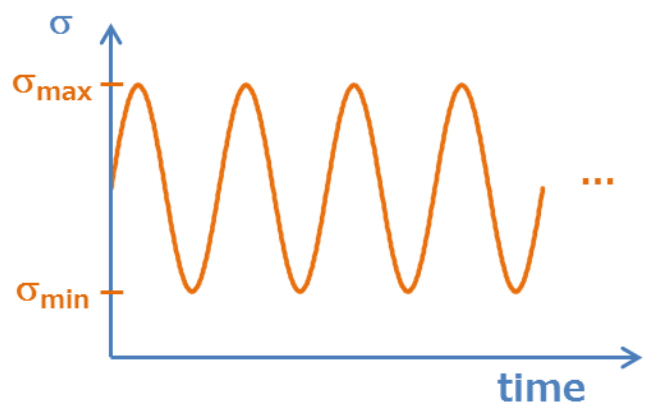
- **Purpose**

In the high field magnet,
REBCO CCs are **repeatedly** subjected to tensile load by electromagnetic force.
→ In order to ensure **long-term reliability**,
it is necessary to evaluate the **fatigue characteristics** of the CC.
→ **Fast cycle repeated tensile tests** are performed in LN_2.

e.g.) 30 years with 10 times excitation per day
→ 100,000 cycle loads

- **Experimental details**

- Test sample : FESC-SCH04 (w/ APC)
- Equipment : Hydraulic servo type fatigue test machine (SHIMADZU: EHF-L) and tensile jig (same as the tensile test setup)
- Control : Stress control
- Repetition frequency : 1 - 12 Hz (sine wave)
- Maximum stress : σ_{max}= 645 - 365 MPa
- Stress ratio : $R = \frac{\sigma_{max}}{\sigma_{min}} = 0.3$ (constant)



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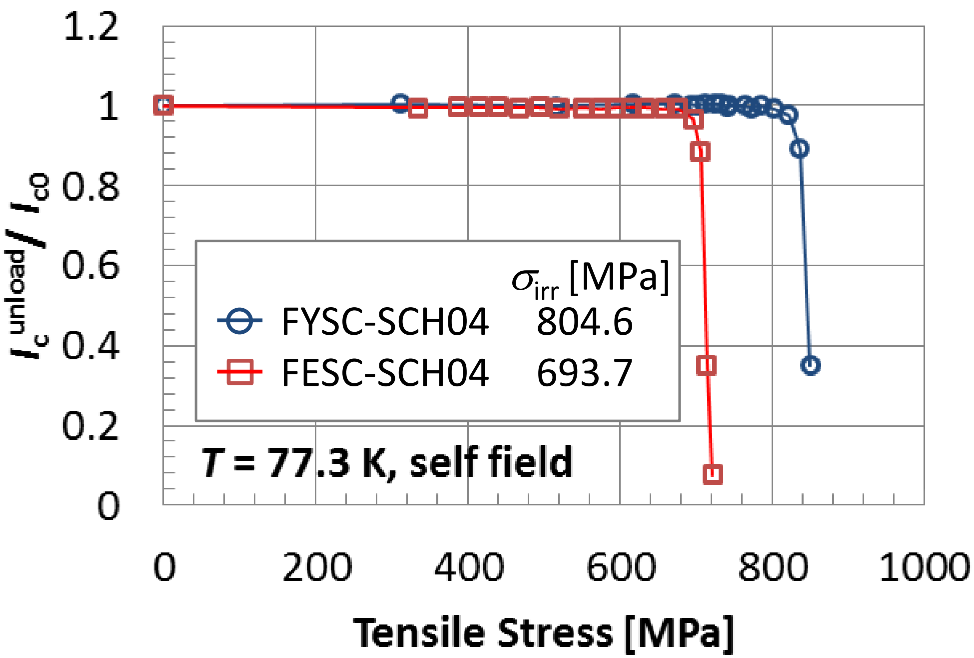
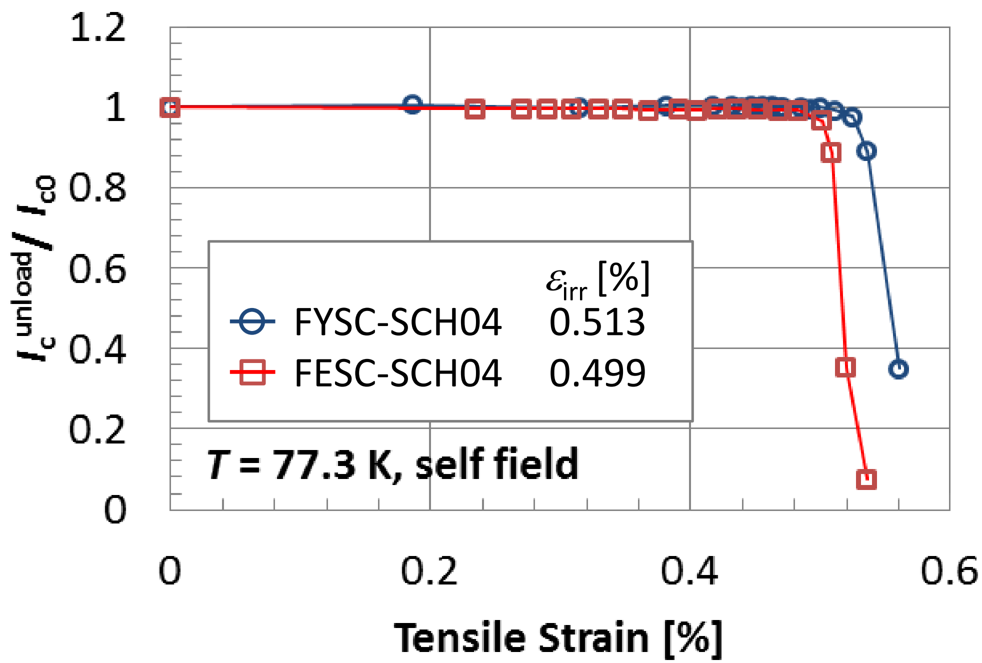
A. Tensile test results

- **Typical data**





Irreversible point, i.e. mechanically degraded point,
were defined as the point **where I_c^{unload} was reduced to 99% of I_{c0}.**

The FESC had
- smaller σ_{irr} value due to the thinner Hastelloy: 75 μm → 50 μm,
- slightly smaller ε_{irr} value due to the thicker REBCO layer: 2.0 μm → 2.5 μm.

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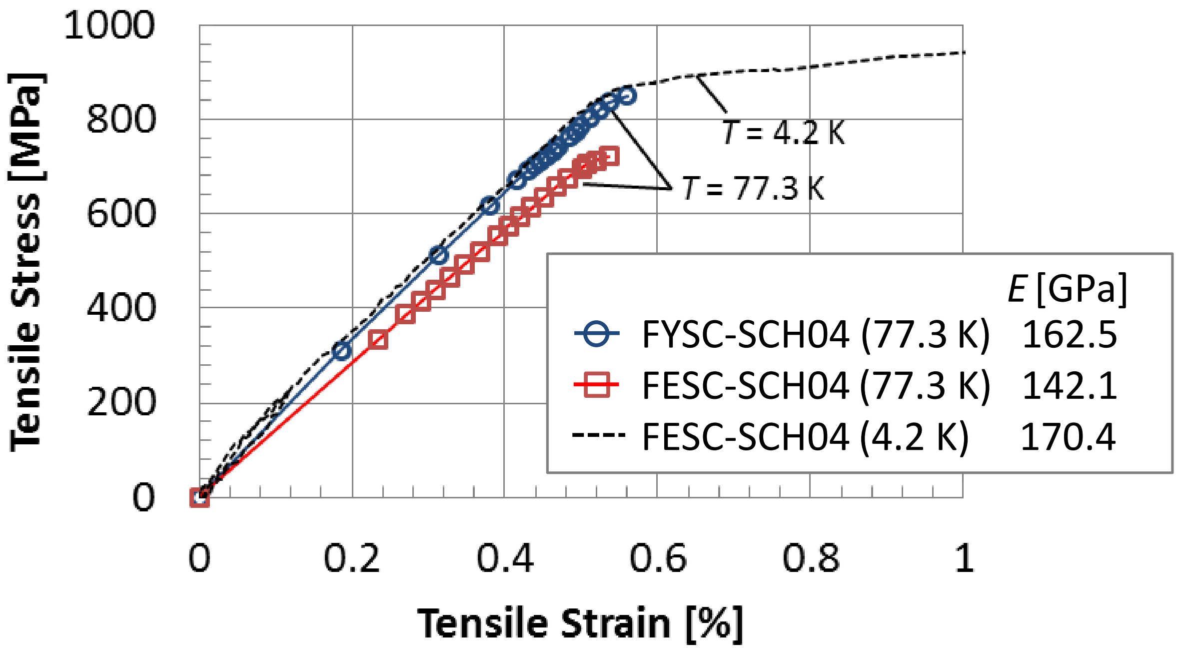
Tensile strength ⇔ J_e

A. Tensile test results

- **Stress-Strain (S-S) curves**

Tensile tests at 4.2 K without I_c measuring and external field were performed using **Katagiri type tensile probe** in LHe.



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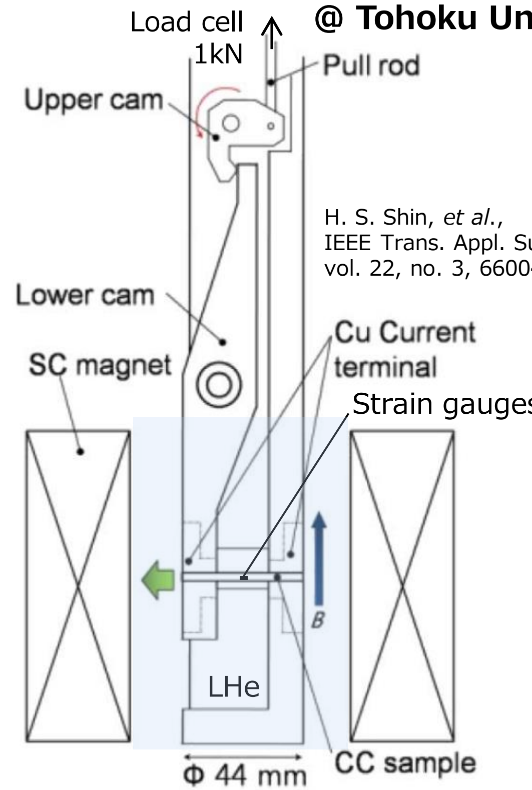


H. S. Shin, *et al.*, IEEE Trans. Appl. Supercond., vol. 22, no. 3, 6600404 (2012).

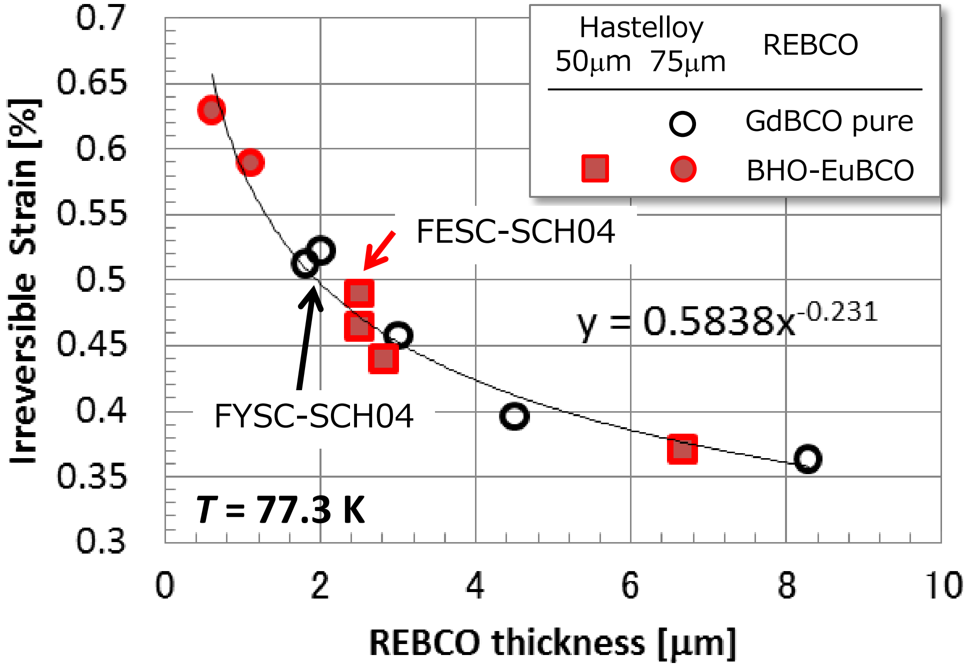
Young's modulus *E* was obtained from the slope in the strain region of **0~0.4%** of S-S curve.

The FESC had
- smaller *E* value due to the thinner Hastelloy: 75 μm → 50 μm,
- increasing *E* value with decreasing temperature: 77 K → 4 K.

B. REBCO thickness dependence

- To investigate in detail the **REBCO thickness dependence** of ε_{irr}, CCs with **greatly different** REBCO thicknesses from 0.6 to 8.3 μm were prepared. Except for REBCO layer, all structures are the same as our standard products.

(4 mm-wide tapes with 20 μm Cu plating)



REBCO thickness: 2.0 → 2.5 μm

ε_{irr} : 0.50 → 0.47 %

- The ε_{irr} nonlinearly decreased with increasing the REBCO thickness.
- It seems that the GdBCO and the BHO-EuBCO are on the same trend.

B. Volume effect

- The **mechanical failure probability** of the REBCO film, as a ceramics, follows the **Weibull distribution** based on the **weakest link model**.

- **The Weibull distribution considering the volume dependence:**

$$F(\varepsilon, V) = 1 - \exp\left[-\frac{V}{V_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^m\right]$$

- **The average fracture strain in the Weibull distribution:**

F: cumulative failure probability
ε: applied strain
V: volume where the strain is applied
m, ε_0: Weibull parameters
V_0: unit volume (e.g. 1 mm^3)
$\Gamma(x)$: Gamma function

$$\bar{\varepsilon} = \varepsilon_0 \Gamma\left(1 + \frac{1}{m}\right)\left(\frac{V}{V_0}\right)^{-\frac{1}{m}} \propto V^{-\frac{1}{m}} \propto (\text{REBCO thickness})^{-\frac{1}{m}}$$

: Volume effect

From the measurement data : ***m* = 4.3.** ⇔ (consistent) e.g.) SmBCO single crystal bulk : ***m* ~ 4.**

N. Sakai, *et al*. SuST, **13** (2000) p.770.

- The REBCO thickness dependence of ε_{irr} is due to the volume effect, which is general phenomena in ceramics.

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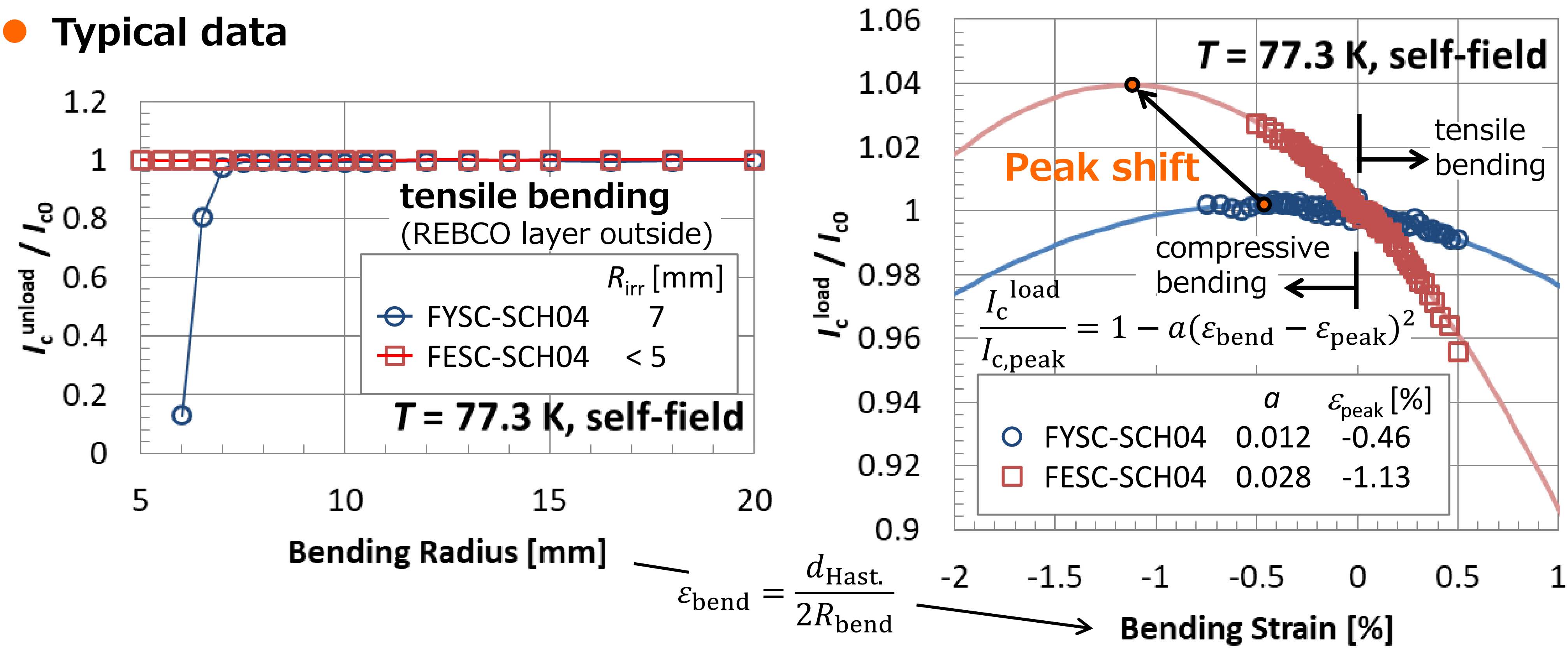
C. Bending test results

- **Typical data**



- The **FESC** can be bent to smaller bending *R* due to thinner Hastelloy.
- **Increased strain sensibility *a*** and **peak shift** by introducing APCs were observed*, but the mechanism has not been well understood.
- The **I_c variation was < 5%** even in the FESC due to the crystal orientation*.

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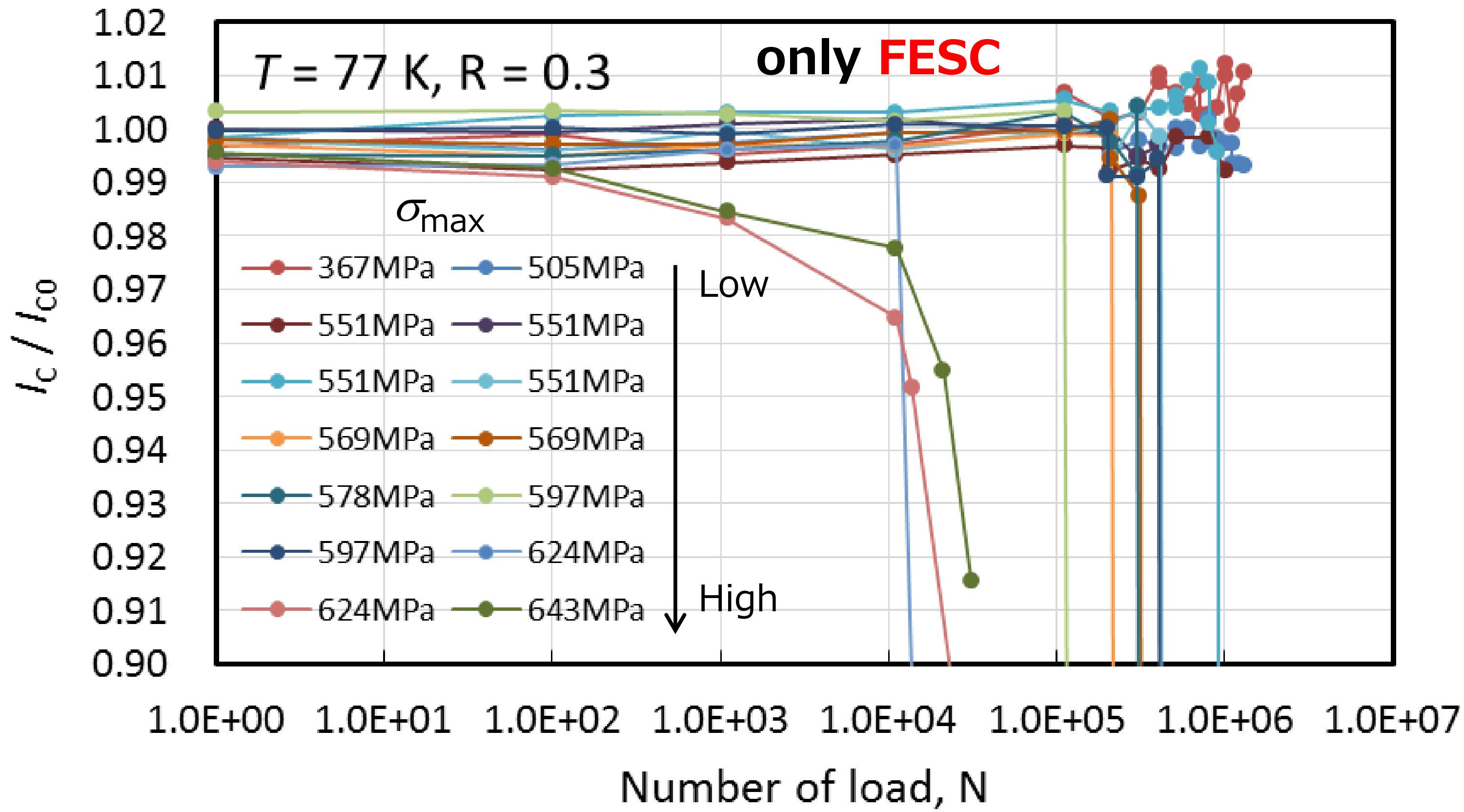
* S. Fujita, *et al.*, *J. Phys.: Conf. Ser.*, vol. 871, 012042, 2017.

D. Cyclic fatigue test results

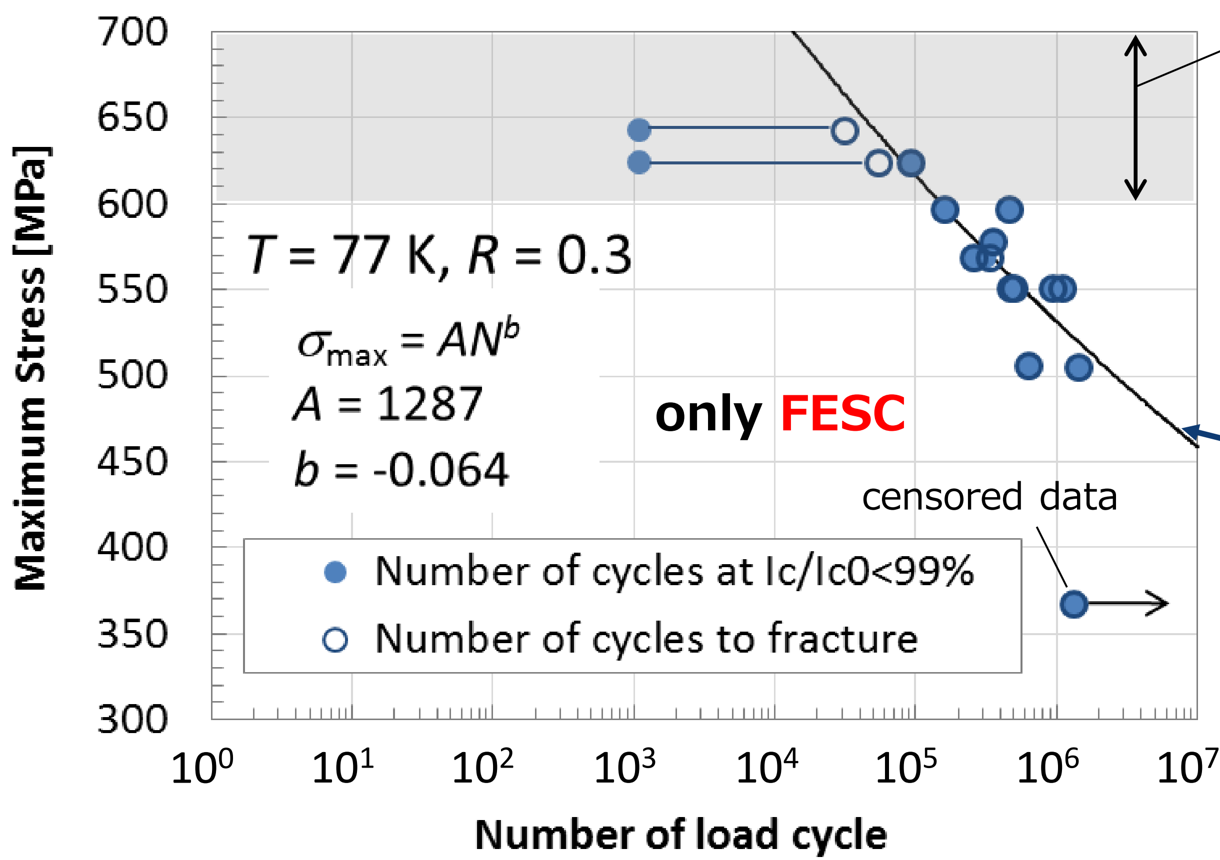
- **Tensile cycle number dependence of I_c**



- For high stress, I_c degradation was confirmed and then fracture.
- For low stress, the fracture occurred before I_c degradation was confirmed.

D. Cyclic fatigue test results

- **S-N curve** (**S**tress - **N**umber of cycle to fracture)



Initial strength:
Single tensile strength, due to the REBCO layer's degradation.
(including variation)

High cycle fatigue with elastic deformation is described by **Baskin's low**:

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} = CN^b$$

$$\sigma_{max} = AN^b$$,with $A = \frac{C}{1-R}$

b, C : material dependent constants

e.g.) 10^7 cycles → 460 MPa

Existence of the fatigue limit?
→ Giga-cycle tests are required.

- **Maintain initial strength up to ~ 10^5 cycles.**
- **Above that, the tensile strength decreases due to fatigue of metal components of the CC.**

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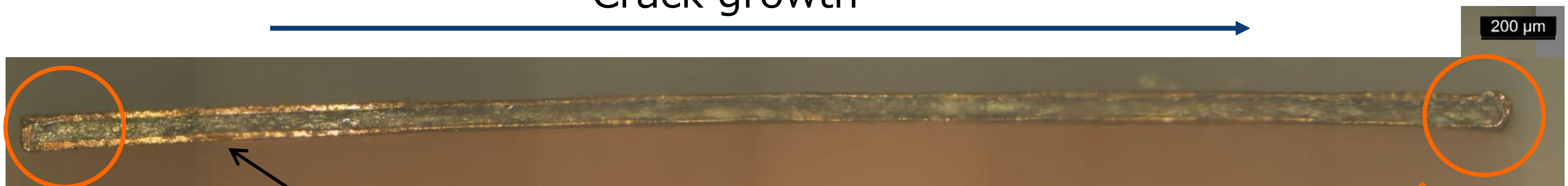
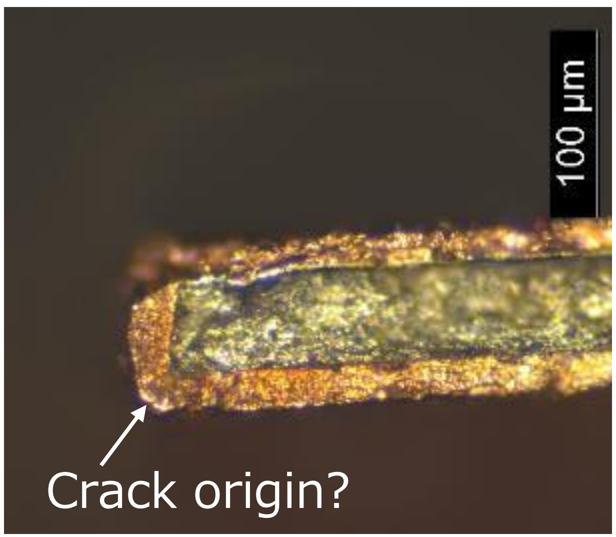
D. Cyclic fatigue test results

- **Observation of fractured sample cross section**

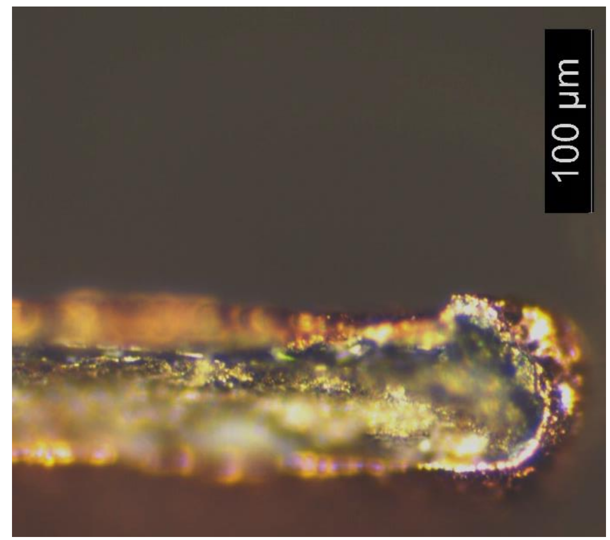
Crack growth



Smooth surface (shiny part)



Relatively smooth fracture surface
(Striation)



Torn-like cross-section
(dimple)

Conclusions

Mechanical properties of mass-production REBCO CCs, including new APC type CC (FESC), were investigated in detail.

- The FESC had smaller irreversible tensile stress and flexibility to bending, because of the thinner Hastelloy of 50 μm which enhances J_e.
- The nonlinear REBCO thickness dependence of irreversible strain was clarified.
  → It can be understood as the volume effect of ceramics.
- By introducing the APCs, the I_c variation with applied strain increased, but it was less than 5%.

  Understanding the mechanism of the strain effects is future work.
- it was confirmed that the tensile strength becomes smaller in repeated stress more than 100,000 cycles, due to the fatigue of metal components of the CC.

Acknowledgements

・A part of this work was performed at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University.

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