Evaluation of various Nb-rod-method Cu-Nb/Nb_3Sn wires designed for practical React-and-Wind coils

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HFLSM
MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

FURUKAWA ELECTRIC GROUP

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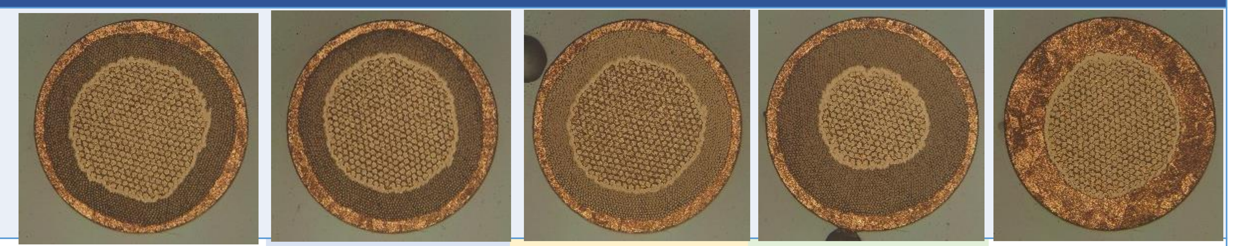
Introduction

- The Cu-Nb/Nb_3Sn wires are applicable to R&W process. The superconducting properties and mechanical characteristics are improved by appropriate pre-bending treatments [1].
- For the primitive design of an advanced 33 T CSM project at Tohoku University, we need to further improve the mechanical strength of Cu-Nb/Nb_3Sn wires [2].
- In this study, we evaluated Cu-Nb/Nb_3Sn wires of various cross-sectional structure to improve the I_c characteristics under applied stress. In addition, we investigated the pre-bending effect of Cu-Nb/Nb_3Sn cables such as a triplex cable and small size Rutherford cables for some uses.

Cu-Nb/Nb_3Sn wires with various cross-sectional design

Wire ID	LK199	LK200	LK201	LK202	LK206
Cross-section					
Cu/Cu-Nb/non-Cu (%)	19/39/42	21/38/41	19/39/42	20/55/25	57/0/43
Nb composition in Cu-Nb (vol%)	20	25	30	25	Non
Diameter of Nb_3Sn Filament bundle (mm)	0.51	0.51	0.51	0.40	0.51
Bronze	Cu-15.7wt%Sn-0.3wt%Ti				
Sn diffusion barrier	Nb				
Wire dia.(mm)	0.80				
Filament dia. (µm)	3.2 (nominal)				
Twist pitch (mm)	24 (direction : Left hand helix)				
Pre-bending pulley diameter (mm)	164/ 125/ 100			134/100/82	164/125/100
Pre-bending strain (%)	±0.3/ ±0.4/ ±0.5				

*Heat-treatment condition : 670 ℃ x 96 hr

Pre-bending process after Nb_3Sn creation heat-treatment in React-and-Wind method

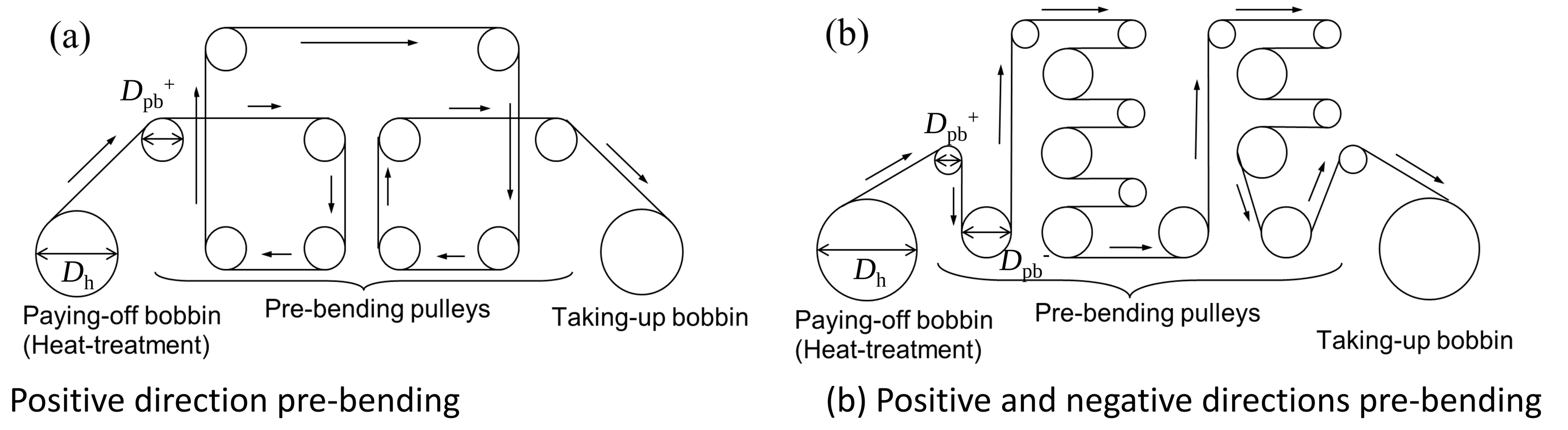


Fig.0. Schematic images of the pre-bending treatment [1]

The pre-bending strain $\varepsilon_{pb}^{\pm}$ defined as the maximum strain applied to the Nb_3Sn filament bundle diameter d_{fb} in the Cu-Nb/Nb_3Sn wire.

$$\varepsilon_{pb}^{\pm} = d_{fb}\left(\pm\frac{1}{D_{pb}^{\pm}} - \frac{1}{D_h}\right)$$

Here, D_{pb}^+ is a pulley diameter for applying a positive pre-bending strain. D_{pb}^- is a pulley diameter for applying a negative pre-bending strain. D_h is the bobbin diameter used during the Nb_3Sn reaction heat-treatment.

Ic performance of Cu-Nb/Nb_3Sn wires under Tensile stress and Transverse compression stress

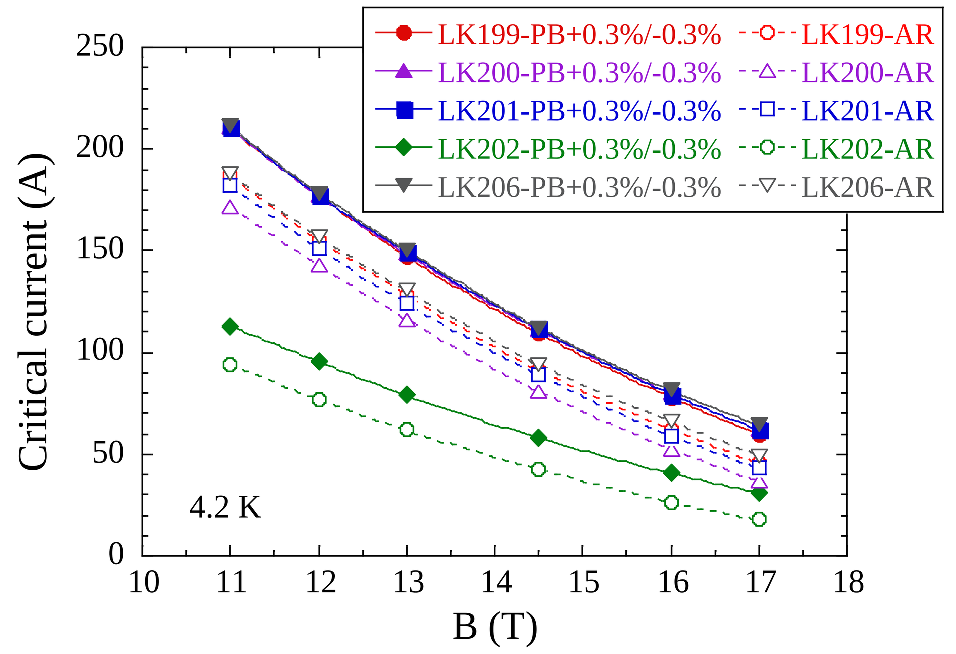


Fig.1. I_c-B characteristics of the various wires (PB: Pre-bent, AR: As-reacted)

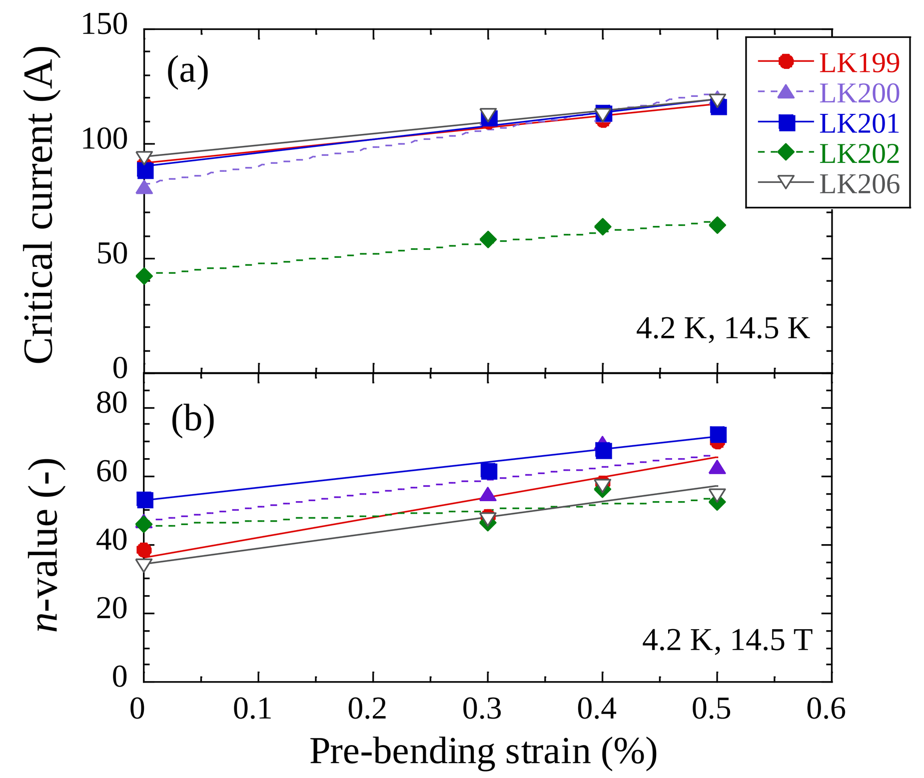


Fig.2. I_c and n-values vs. Pre-bending strain

Fitting parameters of I_c-intrinsic strain characteristics determined by using Summer's formula ; Irreversible strain and irreversible stress

Parameters	25T-CSM		LK199	LK200	LK201	LK202
Pre-bending	As-react	PB±0.3%	PB±0.3%	PB±0.3%	PB±0.3% / ±0.5%	PB±0.3%
B_{c20m} (T)	30.7	32.6	31.1	31.3	31.0 / 29.8	30.4
T_{c0m} (K)	17.8	18.2	19.2	18.4	19.8 / 20.0	19.8
C_0 ($ATmm^{-2}$)	9253	8728	10449	10615	10272 / 11691	10089
a^+ (-)	1661	1783	1465	1366	1553 / 2522	1407
a^- (-)	2311	2104	1890	1873	1652 / 1535	2689
ε_m (%)	0.29	0.15	0.17	0.20	0.23 / 0.09	0.25
ε_{irr} (%)	0.85	0.65	0.71	0.73	0.73 / 0.51	0.62
σ_{irr} (MPa)	485	485	490	490	495 / 500	480

Summer's formula [3]

$$I_c(B,T,\varepsilon_0) = \pi d^2[4(1+\lambda)]^{-1} J_c(B,T,\varepsilon_0) \qquad \varepsilon_0 = \varepsilon - \varepsilon_m \qquad B_{c20}(\varepsilon_0) = B_{c20m}(1-a^{+/-}|\varepsilon_0|^u) \qquad T_{c20}(\varepsilon_0) = T_{c0m}(1-a^{+/-}|\varepsilon_0|^u)^{1/w}$$

$$J_c(B,T,\varepsilon_0) = C(\varepsilon_0)(B_{c2}(T,\varepsilon_0))^{-1/2}(1-t^2)^2 b^{-1/2}(1-b)^2 \qquad C(\varepsilon_0) = C_0(1-a^{+/-}|\varepsilon_0|^u)^{1/2} \qquad b = B/B_{c2}(T,\varepsilon_0) \qquad t = T/T_{c0}(\varepsilon_0)$$

$$B_{c2}(T,\varepsilon_0) = B_{c20}(\varepsilon_0)(1-t^2)[1-0.31t^2(1-1.77\ln t)] \qquad u\ (=1.7) \text{ and } w\ (=3)$$

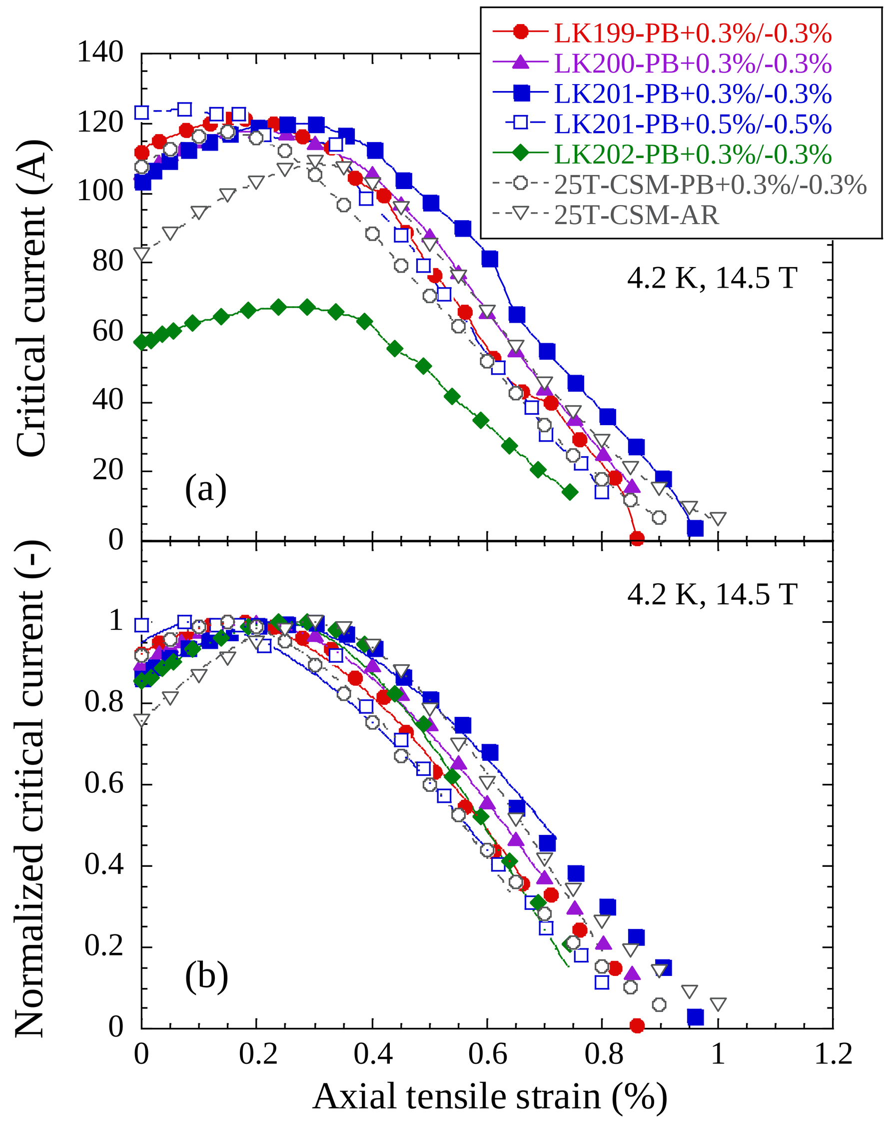


Fig.3. I_c vs. Axial tensile strain (PB: Pre-bent, AR: As-reacted)

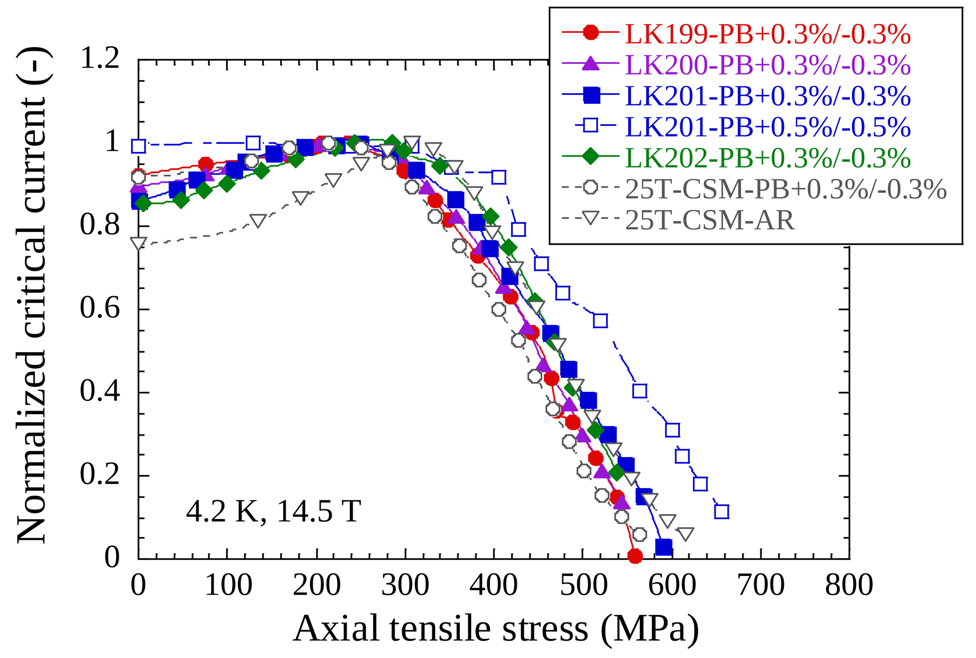


Fig.4. I_c vs. Axial tensile stress

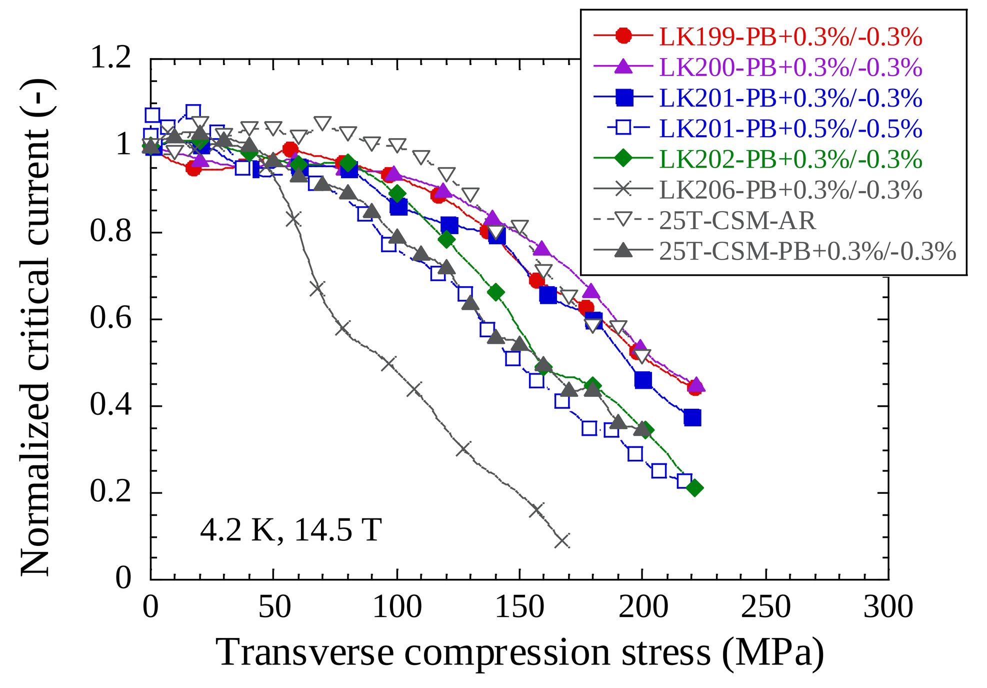


Fig.5. I_c vs. Transverse compression stress

References
1. M. Sugimoto *et al.*, "Development of Nb-rod-method Cu-Nb reinforced Nb_3Sn Rutherford cables for react-and-wind processed wide-bore high magnetic field coils," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. ID. 6000605.
2. S. Awaji *et al.*, "High field cryogen-free superconducting magnet development beyond 30 T with advanced REBCO and high strength Nb3Sn conductors," presented at MT26 (Thu-Mo-Or17-01)
3. L. T. Summers *et al.*, "A model for the prediction of Nb_3Sn critical current as a function of field, temperature, strain, and radiation damage," *IEEE Trans. Magn.*, vol. 27, no. 2, pp. 2041-2044, Mar. 1991.

Small size Cu-Nb/Nb_3Sn cables by using prototype strands [1]

Cable ID		LY151	LY149	LY150
Strand diameter	(mm)	0.80	0.60	0.40
Cu /Cu-Nb/non-Cu	(%)	20 / 35(Cu-20vol%Nb) / 45		
Bronze		Cu-14wt%Sn-0.2wt%Ti		
Diameter of Nb_3Sn fila. bundle	(mm)	0.51	0.38	0.26
Filament diameter (nominal)	(µm)	3.3	2.5	1.7
Twist pitch	(mm)	24	18	12
Cable structure		Triplex	16-stranded-Rutherford	
Dimension Width	(mm)	1.6-1.7	4.80	3.20
Thickness	(mm)		1.14	0.76
Cabling pitch	(mm)	20	48	32
Heat-treatment bobbin diameter	(mm)	270	270	270
Pre-bending pulley diameter	(mm)	164	125	82
Pre-bending strain	(%)	+0.12/-0.50	+0.16/-0.45	+0.22/-0.40

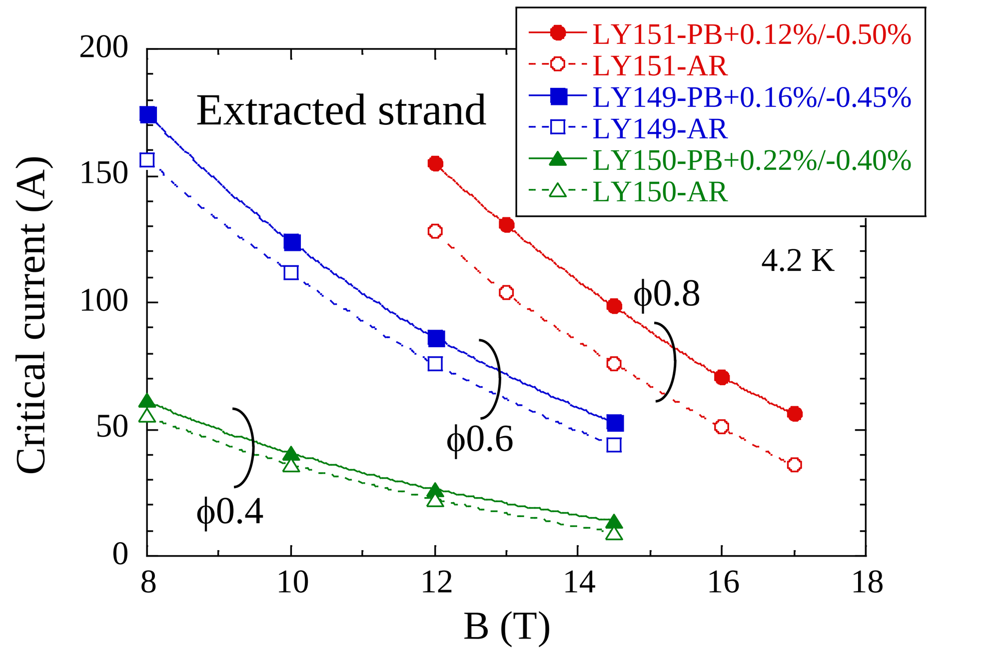
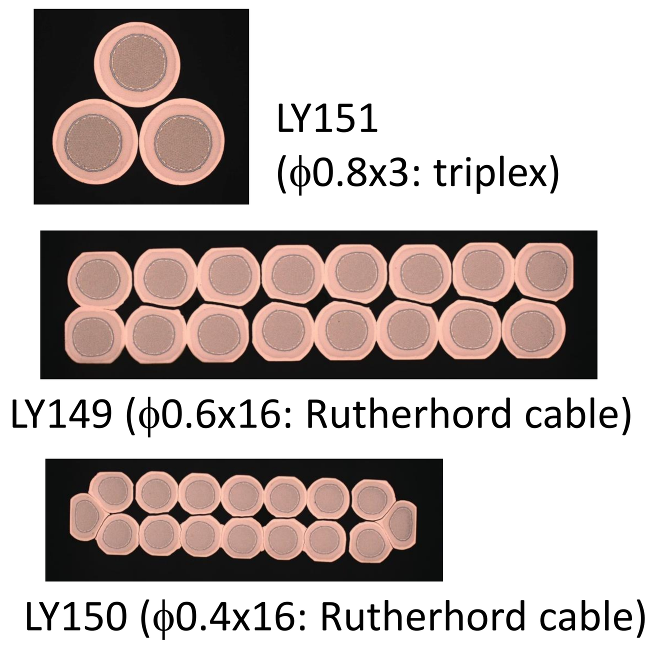


Fig.6. I_c-B characteristics of an extracted strand from reacted Cu-Nb/Nb_3Sn cables



Small size Cu-Nb/Nb_3Sn cables

Summary

- Increment of Nb volume fraction in Cu-Nb reinforcer from 20vol% to 25vol% or 30vol% enhanced the strength of Cu-Nb/Nb_3Sn wires by applying larger pre-bending strains.
- By increasing the volume fraction of the Cu-Nb reinforcer in the Cu-Nb/Nb_3Sn wire to 55vol%, the stress characteristics were improved.
- Based on the required performance of Nb_3Sn coils, it is able to design the cross-sectional structure of the Cu-Nb/Nb_3Sn wires, the pre-bending treatment and Nb_3Sn reaction heat-treatment conditions.
- Cu-Nb/Nb_3Sn wires and cables are expected to be widely used to produce many practical R&W superconducting coils.