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Critical Current Characterization under Pure Bending Strains of Pre-bent Cu-Nb/Nb_3Sn Strands for Practical React-and-Wind Process

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Abstract

- Nb-rod-method Cu-Nb reinforced Nb_3Sn (Cu-Nb/Nb_3Sn) wires have been successfully developed for commercialization of the React-and-Wind (R&W) processed Nb_3Sn coils. Superconducting performance of the Cu-Nb/Nb_3Sn wires are improved by applying the pre-bending treatment at room temperature, because of releasing the residual stress of Nb_3Sn filaments (pre-bending strain effects).
- The purpose of this study is to obtain information of the efficient use of the pre-bending strain effects for optimizing critical current (I_c) characteristics under pure bending strain on the R&W coil design.
- The Cu-Nb/Nb_3Sn strands of diameter 0.8 mm were heat-treated at 670 ˚C for 96 hours on stainless steel grooved cylindrical holders of different radii 10.1-32.1 mm. After the half of the reacted strands were applied repeating pre-bending strain ±0.5%, each of the pre-bent strands and as-reacted (without pre-bent) strands was transferred to a Ti-6Al-4V alloy grooved cylindrical holder of radius 15.6 mm, and those I_c measurements were carried out under applied pure bending strains range from -0.9% to +0.84% at 11-17 T, 4.2 K.
- As a result, the pre-bent strand showed no deterioration of I_c in the applied pure bending strain of range of +0.5% from -0.5% and had larger I_c than that of as-reacted strand at no pure-bending strain. In this paper, the I_c enhancements of the pre-bent Cu-Nb/Nb_3Sn strands under pure bending strains are analyzed by using the I_c characteristics under axial strains.

Nb-rod-method Cu-Nb/Nb_3Sn strands

Advantage of Nb-rod-method Cu-Nb reinforced Nb_3Sn strand

- ✓ Mass productivity is superior to In-situ-method.
- ✓ Design of the equivalent diameter of Nb-rod, the placement, the volume ratio for control of the properties.
- ✓ High I_c characteristics under the large axial tensile stress
- ✓ High RRR, because impurities are not easily incorporated into the Cu matrix.

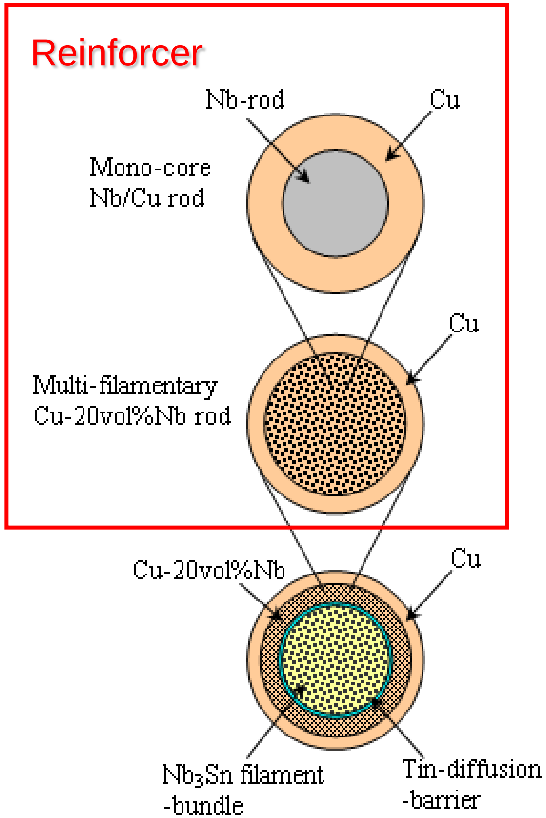

TABLE I MAIN PARAMETERS OF CU-NB/NB_3SN STRANDS

Items	Unit	Parameter
Superconductor	-	Bronze- processed Nb_3Sn
Reinforcement	-	Nb-rod-method Cu-20vol%Nb
Bronze	-	Cu-14wt%Sn-0.2wt%Ti
Sn diffusion barrier	-	Ta
Filament diameter	μm	3.3
Diameter	mm	0.80
Filament region dia.	mm	0.51
Volume fraction Cu / Cu-Nb / non-Cu (Ta)	%	18 / 37 / 45(5)
Twist pitch /direction	mm	24 / Left hand helix

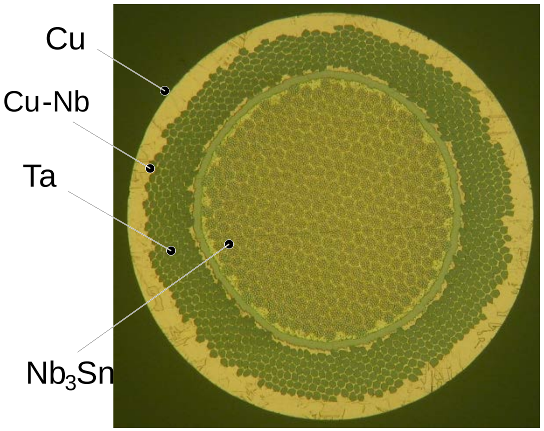

Fig. 1. Cross-section of Nb-rod-method Cu-Nb/Nb_3Sn strand

I_c characteristics of Cu-Nb/Nb_3Sn strands under axial tensile strain

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TABLE II Strain characteristics Determined by using ITER 2008 strain scaling parameters for the tested strands

	Parameter	As-reacted	Pre-bent
C_{a1}	Strain fitting constant	43.84	48.17
C_{a2}	Strain fitting constant	9.37	1.42
ε_{0a}	Residual strain component	0.113%	0.175%
ε_m	Tensile strain at the maximum properties	-0.291%	-0.143%
B_{c2m0}	Upper critical field at zero temperature and strain (T)	35.00	34.84
T_{cm0}	Upper critical temperature at zero field and strain (K)	11.26	10.49
C	Scaling constant (AT)	99823	85025
p	Low field exponent of the pinning force	0.834	0.750
q	High field exponent of the pinning force	2.195	1.819

$$I_c(B,T,\varepsilon_0) = \pi d^2 \left[4(1+\lambda)\right]^{-1} J_c(B,T,\varepsilon_0)$$

$$J_c(B,T,\varepsilon) = C B^{-1} s(\varepsilon)(1-t^{1.52})(1-t^2) b^p (1-b)^q$$

$$B^*_{C2}(T,\varepsilon) = B^*_{C20m} s(\varepsilon)(1-t^{1.52})$$

$$T^*_C(T,\varepsilon) = T^*_{C0m} s(\varepsilon)^{1/3}\left(1 - B/B^*_{C2}(0,\varepsilon)\right)^{1/1.52}$$

$$s(\varepsilon) = 1 + \left(\left(C_{a1}\left(\sqrt{\varepsilon_{sh}^2+\varepsilon_{0a}^2} - \sqrt{(\varepsilon-\varepsilon_{sh})^2+\varepsilon_{0a}^2}\right) - C_{a2}\varepsilon\right)\right.$$

$$\times\left(1 - C_{a1}\varepsilon_{0a}\right)^{-1}$$

$$\varepsilon_{sh} = C_{a2}\varepsilon_{0a} \Big/ \sqrt{C_{a1}^2 - C_{a2}^2}$$

$$\varepsilon = \varepsilon_{applied} + \varepsilon_m$$

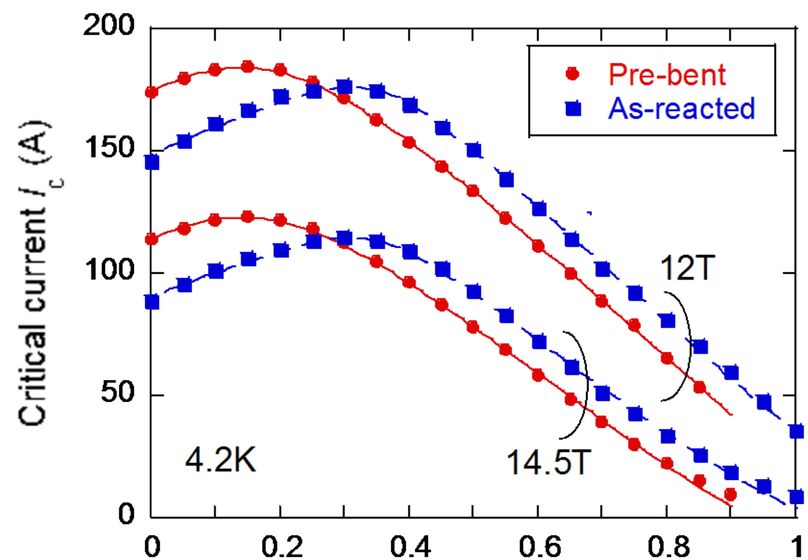

Fig. 2. I_c characteristics of Cu-Nb/Nb_3Sn strands as a function of axial tensile strain. Solid and dashed lines are calculated by using ITER2008 strain scaling parameters of TABLE II.

Reference

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Heat treatments, pre-bending and pure-bending process

Pre-bending strain

$$\varepsilon_{pb}^{+} = \frac{d_0}{2}\cdot\left(\frac{1}{R_h} - \frac{1}{R_{pb1}}\right)$$

$$\varepsilon_{pb}^{-} = \frac{d_0}{2}\cdot\left(\frac{1}{R_h} - \frac{1}{R_{pb2}}\right)$$

Pure-bending strain

$$\varepsilon_{pure-bend\,peak} = \frac{d_b}{2}\cdot\left(\frac{1}{R_h} - \frac{1}{R_b}\right)$$

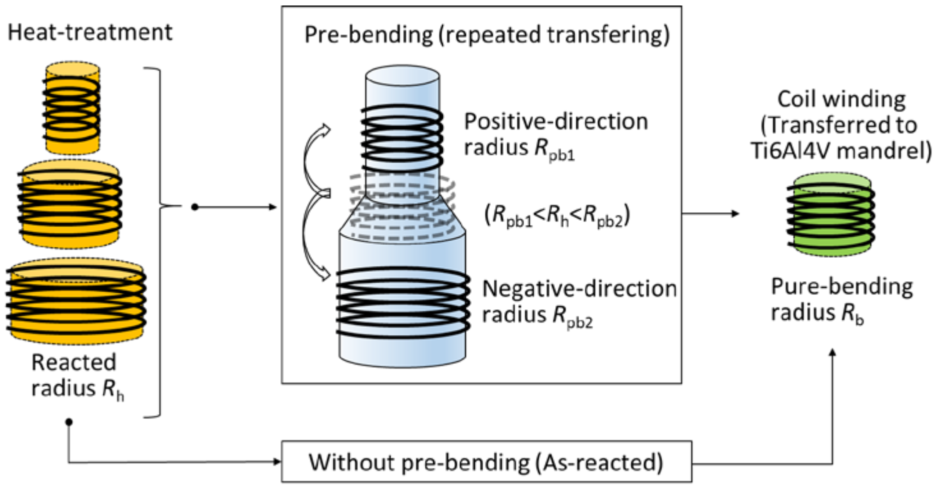

Fig. 3. Schematic image of Heat treatments, pre-bending and the pure-bending process.

TABLE III
Process condition on Heat treatment and Pre-bending

Heat-treatment	Pre-bending for ε_{pb} =±0.5%		Pure-bending	
R_h (mm)	R_{pb1} (mm)	R_{pb2} (mm)	R_b(mm)	$\varepsilon_{pure-bend.}$(%)
32.1	22.9	54.2	15.6	+0.84
24.6	18.8	35.8	15.6	+0.60
19.6	15.8	26.1	15.6	+0.33
15.6	13.1	19.5	15.6	0
12.9	11.2	15.5	15.6	-0.34
11.3	10.0	13.2	15.6	-0.62
10.1	9.0	11.6	15.6	-0.90

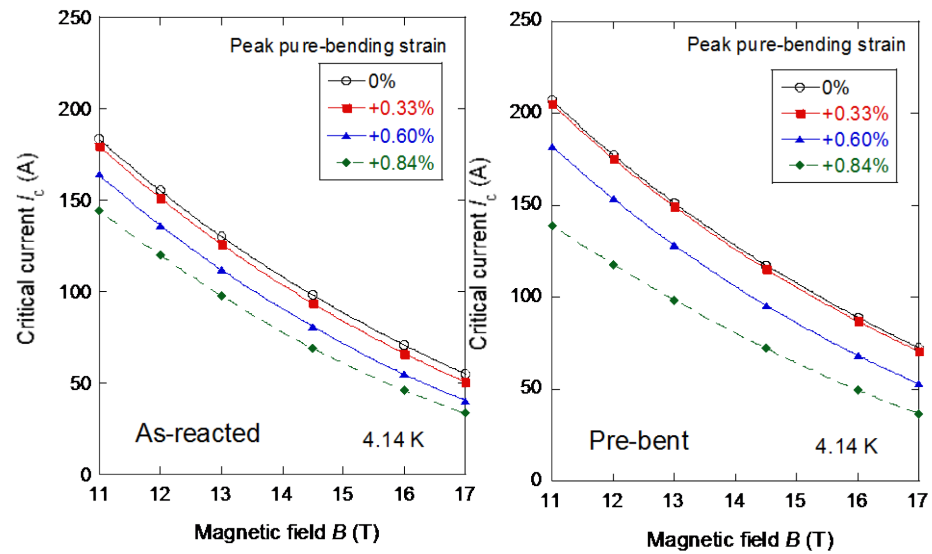

Fig. 4. I_c-B characteristics under pure-bending strains of Cu-Nb/Nb_3Sn strand.

Pure-bending strain dependence of I_c and *n*-value

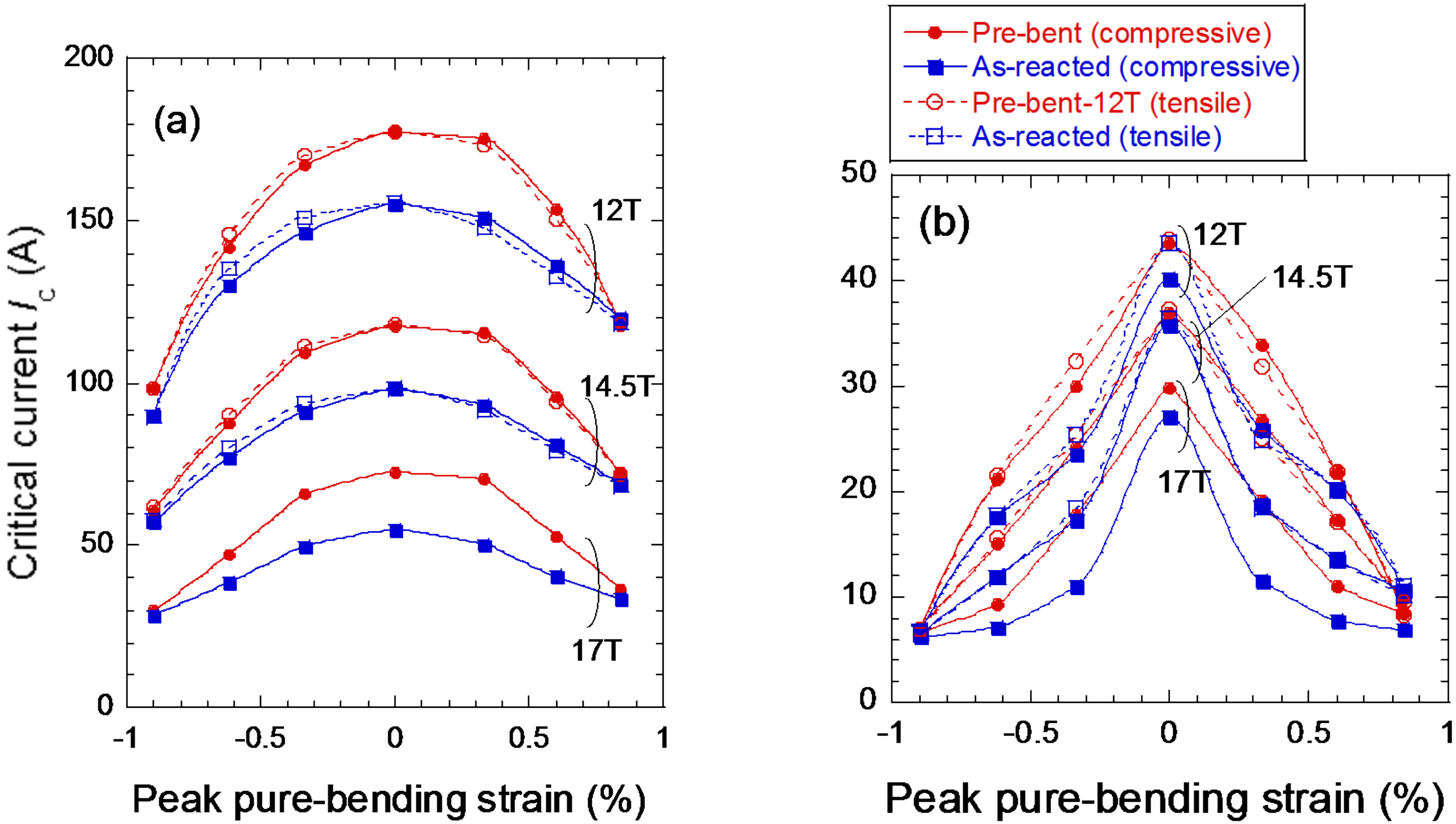

Fig. 5. I_c characteristics under pure-bending strains of Cu-Nb/Nb_3Sn strand.
(a) I_c values (b) n-values

The relationship between I_c and the pure bending strain is shown in Fig. 5(a), and that of *n*-values is shown in Fig. 5(b). The pre-bent strands showed no deterioration of I_c in the applied pure bending strain of range of +0.5% from -0.5% and had larger I_c than that of as-reacted strand at no pure-bending strain. The I_c increase of pre-bent strands were conformed at 12-17 T. The degradation of *n*-values occurred at -0.90% because the peak pure-bending strain was larger than the irreversible strains e_{irr} =0.85% of this strand. The Nb_3Sn filaments on the inside of the Ta barrier are supposed to be partially broken.

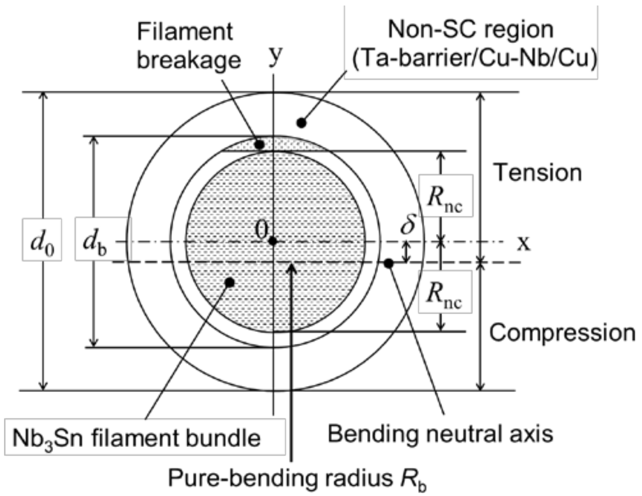

Fig. 6. Cross-section model of non-copper showing the neutral axis shift of δ.

◆ Perfect current transfer model

$$I_c = 2\int_{-R_{nc}}^{R_{nc}} j_c(\varepsilon_y)\sqrt{R_{nc}^2 - y^2}\,dy$$

$$\varepsilon_y = \varepsilon_0 + \varepsilon_{by} \qquad \varepsilon_{by} = (y+\delta)/(R_b-\delta)$$

◆ No current transfer model

$$I_c = 2\pi\int_0^{R_{nc}} \left\{\min\left|j_c(\varepsilon_y)\right|_{\varepsilon_y=\varepsilon_0-\varepsilon_{by}}^{\varepsilon_y=\varepsilon_0+\varepsilon_{by}}\right\} y\,dy$$

$$\varepsilon_{by} = \begin{cases} -(y+\delta)/(R_b-\delta) & \text{for } j_c(\varepsilon_0 - y/R_b) < j_c(\varepsilon_0 + y/R_b) \\ +(y+\delta)/(R_b-\delta) & \text{for } j_c(\varepsilon_0 - y/R_b) > j_c(\varepsilon_0 + y/R_b) \end{cases}$$

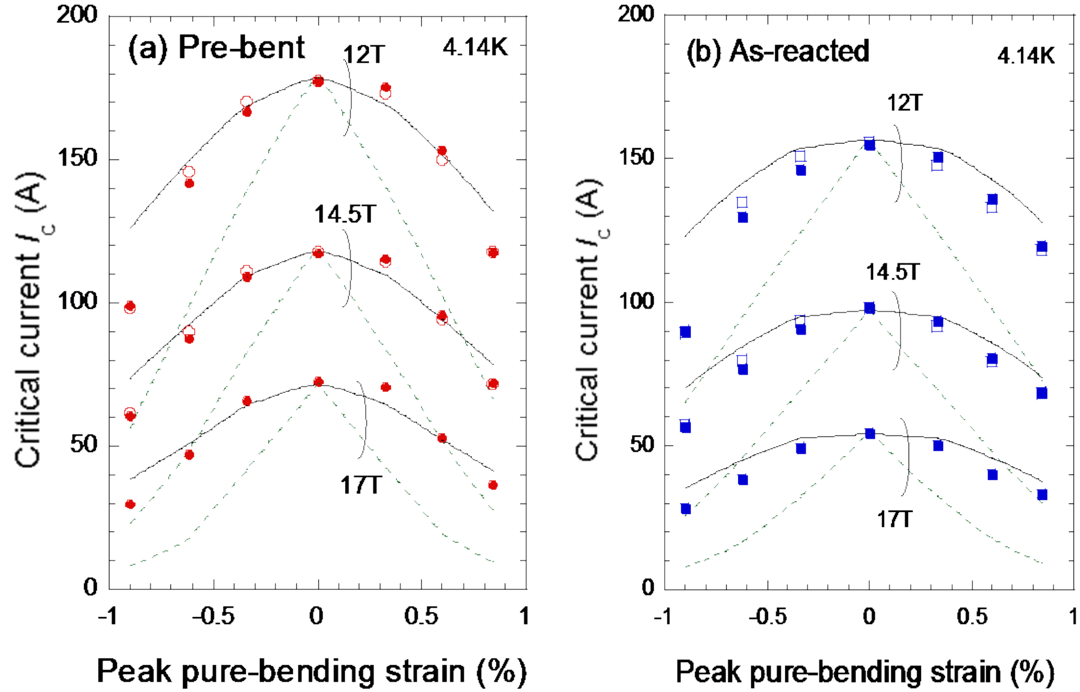

Fig.7. Comparison between the measured I_c and calculated I_c values of (a) Pre-bent strands and (b) As-reacted strands. Perfect current transfer model (solid lines) fit well comparing to no current transfer model (dashed lines).

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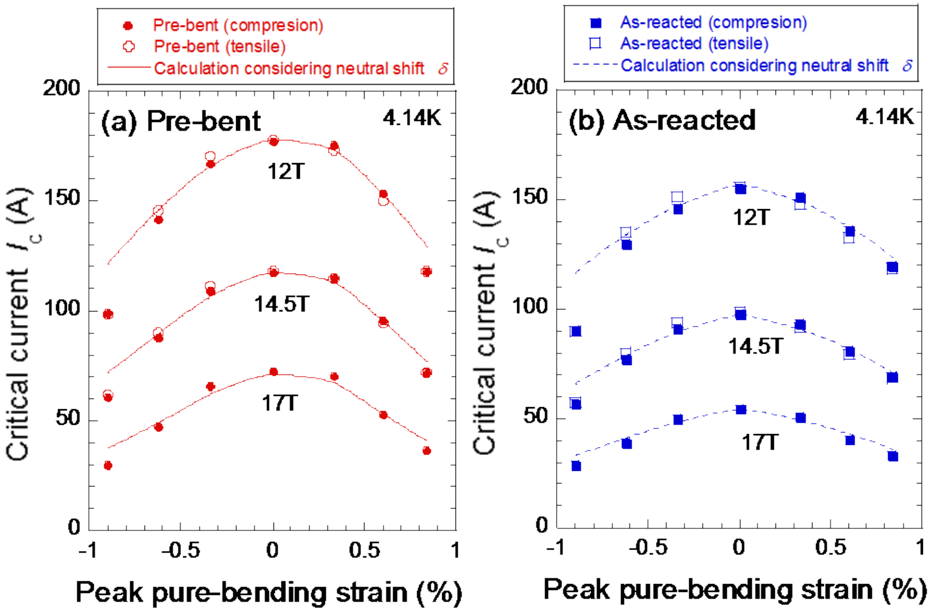

Fig. 8. I_c values calculated considering of neutral shift δ

The neutral axial shifts will be caused by the spring back effects of the strand after the pure-bending process. The neutral shift δ at positive pure-bending and that at negative pure-bending of the pre-bent Cu-Nb/Nb_3Sn strands were assumed to be -0.09 mm and -0.02 mm. On the other hand, those of as-reacted strands were assumed to be +0.03 mm and -0.04 mm. The difference will be related to residual strain.

Summary

- Critical current characteristics under pure bending strains of pre-bent Cu-Nb/Nb_3Sn strands were investigated.
- I_c values of pre-bent strands were increased at pure-bending strain from -0.5% to 0.5% by the pre-bending treatment of ε_{pb} = ±0.5% than those of the as-reacted strands.
- Analysis based perfect current transfer model can quantitatively explain the peak pure-bending strain dependence of I_c considering neutral axis shifts.
- It was confirmed that the appropriate pre-bending process of the Cu-Nb/Nb_3Sn wires is very useful for practical manufacturing of R&W processed Nb_3Sn magnets.