Experimental and Numerical Study on Crack Evolution of Nb Barriers Causing Ic Deterioration in Multi-filament MgB2 Strands during Cabling Process for Large-scale Energy Storage Coils

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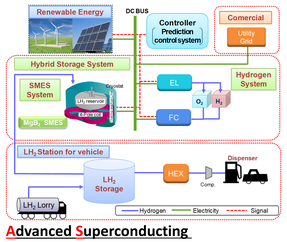
Background

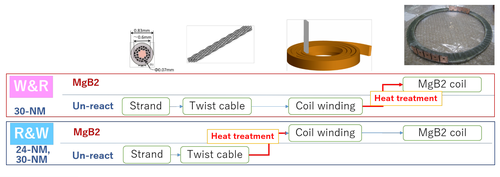
- In order to reduce green house gas emission and realize the sustainable society, great number of renewables in electric power system need to be introduced.
- One of the big issues of introducing renewable energy sources is uncontrollable, changing output power, depending on the weather.
- Our group have been proposed new power system reducing carbon footprint named **A**dvanced **S**uperconducting **P**ower **C**onditioning **S**ystem (**ASPCS**) which includes renewable resources, superconducting power applications and Liquid Hydrogen(LH2) storage and distribution system.
- **Along with the wide-spreading Hydrogen energy use, the superconducting magnetic energy storage (SMES) device made of MgB2 has been rapidly attracting the attention with respect to its Tc = 39 K, which is well above the boiling temperature of LH2.**
- **In this project, Our group will perform the feasibility study of MgB2 material applied to large-scale conductor and SMES coils.**



Advanced Superconducting Power Conditioning System (ASPCS)

- ✓ **MgB2 coils wound with 600A Rutherford type conductors are designed introducing React-and-Wind (R&W) , Wind-and-React (W&R) processes.**
- ✓ **Through the conductor and coil test campaigns, undesired deteriotations in strand Ic were observed, so the origin must be cleared for**

MgB2 Conductors and SMES Coils: Applying Different Manufacturing Methods for Feasibility Study



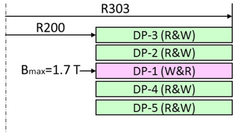
	fabrication	Strand	Num. of Strand	Type of Conductor	Twist Pitch [mm]	Cross Section Of Conductor	Max. Bending Strain (Conductor)	Max. Bending Strain (Coil)
DP1	W&R (Wind & React)	30NM	8 MgB_2 + 4 CuZn	Rutherford with former	51		1.25% < 4%	1.38% < 4%
DP2	R&W (React & Wind)	24NM	10	Rutherford w/o former	81		2.26% < 4%	0.19% < 0.23%
DP3	R&W (React & Wind)	30NM	12	Rutherford w/o former	82		2.14% < 4%	0.17% < 0.23%

Features

W & R
- ✓ Large margin of acceptable strain
- ✓ Well-experienced
- × Whole coil Heat-treatment, needs tolerable insulation even at ～750 ℃)

R & W
- ✓ Easy to refine the coil dimension
- ✓ Easy for inter-layer insulation
- × severe margin of bending strain (< 0.23%)

MgB2 SMES Coil

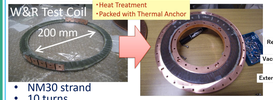


SMES coil :
Stacked 5 DPs
1 W&R DP+4 R&W DPs

- Iop= 600 A at 22K, 1.7 T
- E = 30 kJ
- ID = 400 mm
- OD= 606 mm
- Turns: 72 for W&R DP, 110 for R&W DP

Setups for demonstration

W&R Test Coil

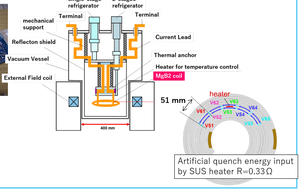


- NM30 strand
- 10 turns
- Conduction Cooling

ID=200mm, 10 turns Single
Iop=300-500 A, B=0-5 T

T. Yagai, et al. Cryogenics 96 (2018) 75-82

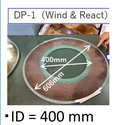
Ic-B-T characteristic



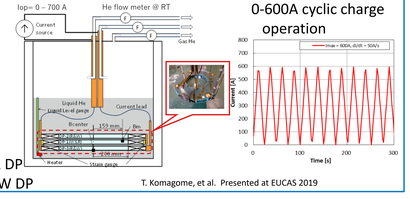
Artificial quench energy input by SUS heater R=0.33Ω

Ic-B-T characteristics of W&R test coil have been obtained
Ref, S. Mizuno, et al. IEEE Trans. Appl. Supercond. **28**, No.3, 2018 ID#4602505

DC, AC current tests for DP1-2-3 coils



- ID = 400 mm
- OD= 606 mm
- Turns: 72 for W&R DP, 110 for R&W DP

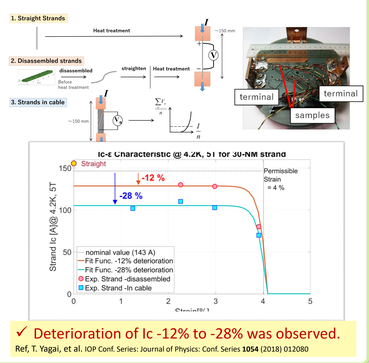


T. Komagome, et al. Presented at EUCAS 2019

Charge test for stacked DPs has also been performed.
Ref, T. Yagai, et al. IOP Conf. Series: Journal of Physics: Conf. Series **1054** (2018) 012080

✓ **Although the coils worked well, undesired deteriorations in Ic were observed**

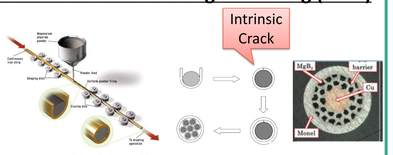
Confirmation of Ic degradation



✓ Deterioration of Ic -12% to -28% was observed.
Ref, T. Yagai, et al. IOP Conf. Series: Journal of Physics: Conf. Series **1054** (2018) 012080

Strand Manufacturing - CTFF

Continuous Tube Forming and Filling (CTFF)



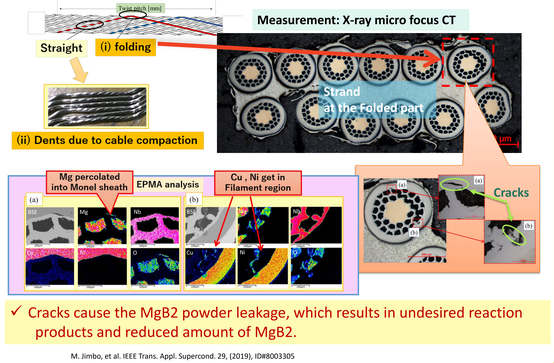
M. Tomsic, et al. Int. J. Appl. Ceram. Technol. 4[3] 250-259 (2007)
D. Patel, et al. Cryogenics 63 160-165 (2014)

(i) Continuous Nb strip is used
(ii) One through the tube shaping dies, the plate is formed into "U" shape
(iii)After composite powder is inserted, the closing dies gradually close off the tube, forming "O" shape.

- ➢ Long-length production (～10 km)
- ➢ Commercially viable

✓ Intrinsic Crack in Nb barrier is inevitable

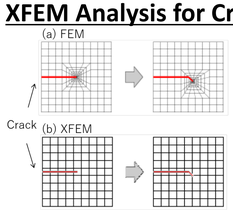
Experimental Investigation on Crack evolution



✓ Cracks cause the MgB2 powder leakage, which results in undesired reaction products and reduced amount of MgB2.

M. Jimbo, et al. IEEE Trans. Appl. Supercond. 29, (2019), ID#8003305

XFEM Analysis for Crack Evolution



(a) FEM based on linear Fracture mechanics
- "Crack" evolves at boundaries between elements
- Fine meshes, elements of high-resolution are needed around the tip of the "Crack".

(b) XFEM (Extended Finite Element Method)
- "Crack" would be evolved even in the elements, so there is no restriction on setting the positions.
- No fine meshes are needed, while the crack criterion is based on linear fracture mechanics.

$$\boldsymbol{u}(\boldsymbol{x},t)=\sum_{I\in Q} N_I \boldsymbol{U}_I \quad \Rightarrow \quad \boldsymbol{u}(\boldsymbol{x},t)=\sum_{I\in Q} N_I\{\boldsymbol{U}_I + h(\boldsymbol{x},t)\bar{\boldsymbol{U}}_I\}$$

$\boldsymbol{u}$: physical quantity, Q: finite element includes x, I: Node groups
$\boldsymbol{U}_I$: Node quantity, N_I: Interpolation function
$\bar{U}_I$: freedom of node, $h(x,t)$: enrichment function

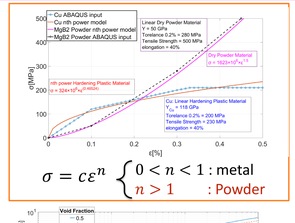
Introduction of discontinuity

✓ **Two-dimensional XFEM analysi is performed, saving CPU time even in the nonlinear simulation.**

Mechanical Properties

	Cu	Monel (Ni Alloy)	Nb	MgB2 (Powder)
Young's Modulus [GPa]	118	185	105	50
0.2% proof stress [MPa]	200	800	85	230
Max. Principle Stress [MPa]	250	1000	124	1

Stress-Strain curve: n^{th} power hardening Plastic



$$\sigma = c\varepsilon^n \quad \begin{cases} 0 < n < 1 : \text{metal} \\ n > 1 : \text{Powder} \end{cases}$$

Tensile splitting strength of the compressed powder

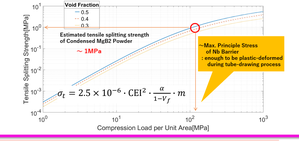
$$\sigma = \alpha\varepsilon\text{: linear approximation}$$

$$m = V_f \log_e \frac{1+\alpha/\sigma}{\alpha/\sigma} - \log_e \frac{1+\alpha/\sigma}{1-V_f+\alpha/\sigma}$$

$$\sigma_t = 2.5\times10^{-6}\cdot \mathrm{CEI}^2 \cdot \frac{\alpha}{1-V_f}\cdot m$$

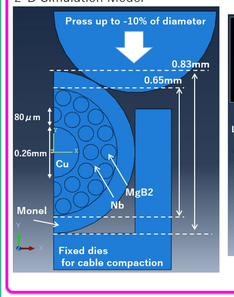
σ_t: Tensile Splitting Strength
V_f: Void Fraction
CEI : grinding progress index ～50 for 100μm powder

K. Matsui, et al. Journal of the Society of Materials Science, Japan, 20, 762-766, 1971

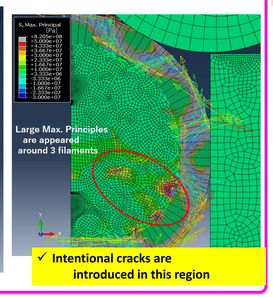


Simulation Model

2-D Simulation Model

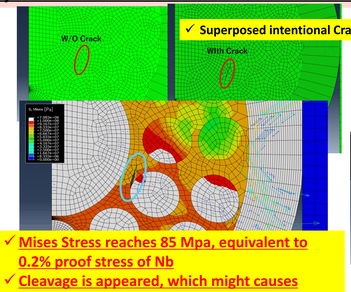


-10% press w/o Crack



✓ Intentional cracks are introduced in this region

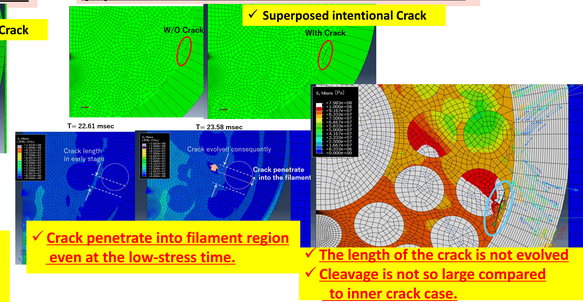
(i) Crack around an inner filament



✓ Superposed intentional Crack

- ✓ Mises Stress reaches 85 Mpa, equivalent to 0.2% proof stress of Nb
- ✓ Cleavage is appeared, which might causes the leakage of MgB2 powder

(ii) Crack around an outer filament



✓ Superposed intentional Crack

- ✓ Crack penetrate into filament region even at the low-stress time.
- ✓ The length of the crack is not evolved
- ✓ Cleavage is not so large compared to inner crack case.

Summay

- The coils made with R&W and W&R methods for SMES device worked well as designed.
- Not small Ic degradations have come to light, CT observation unveiled the damage of Nb barriers due to radial deformations.
- To verify the barrier damage, XFEM analysis was conducted and showed cleavage and crack evolution in the Nb and filament.
- Simulation of the cleavage evolution in the Nb barrier should be improved for explaining actual crack situation.