Report on Over 25 000 Cycles Fatigue Test Results of a REBCO HTS Coil and Crossover Joint in a 7 T Background Magnetic Field at 4.2 K

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***Abstract*—This study presents experimental results on the fatigue characteristics of a REBCO coil and crossover joint, aiming to determine whether they can withstand cyclic loading up to the condition of the 40 T superconducting magnet's design fatigue limit. A pair of REBCO coils were wound with SP (SuperPower) 1013, using copper and stainless steel tape as co-winding materials. The crossover sample, designed to the 40 T superconducting magnet baseline specifications and composed of four Bi2223 (Sumitomo Type H) tape conductors soldered to a stainless steel foil, was mounted to the outermost turn of the REBCO coil. Both the coil and crossover were subjected to cyclic loading by ramping the current up and down in a 7 T background magnetic (BM) field at 4.2 K, with over 25,000 cycles applied. The electromagnetic strain between the outermost turn of the REBCO coil and the crossover joint was estimated numerically, considering the screening current distribution.**

***Index Terms*—Crossover joint, fatigue test, HTS coil, SCF, stress, strain.**

I. Introduction

HIGH temperature superconducting (HTS) tape is considered an essential material for constructing high-field magnets worldwide [1], [2], [3], [4], [5]. To date, many research institutions have been actively engaged in studies on high-field magnets using HTS tapes. The National High Magnetic Field Laboratory (NHMFL) is also in the process of designing a 40 T superconducting magnet for future installation in its DC magnetic field facilities, and through years of research, has acquired the necessary technologies to transition the 40 T superconducting magnet project into its construction phase. The 40 T superconducting magnet, once completed, will serve as a "user magnet" designed to provide a high-field environment for scientific research. One of the key goals is to ensure stable operational performance by undergoing approximately 50000 charge-discharge cycles over a 10-year period. Therefore, it is essential to investigate the fatigue properties of various components that make up the HTS magnet, and extensive fatigue property testing has been conducted on multiple test magnets to meet this need. Based on this background, this study presents the experimental results on the fatigue properties of HTS tapes and joints. Two single pancake-type coils were fabricated using HTS tape from SuperPower (SP), and the connection between the two pancake coils was realized using a crossover joint made from Sumitomo Bi-2223 tape. The fabricated coils and crossover joints underwent over 50000 cycles in an 8 T cryogenic cooled magnet at 4.2 K. Damage was assessed by monitoring the voltage changes in each coil and crossover joint. Furthermore, based on the experimental conditions, the screening current distribution and strain distribution in the coils were numerically modeled, allowing us to estimate the strain experienced by the coils and crossover joints.

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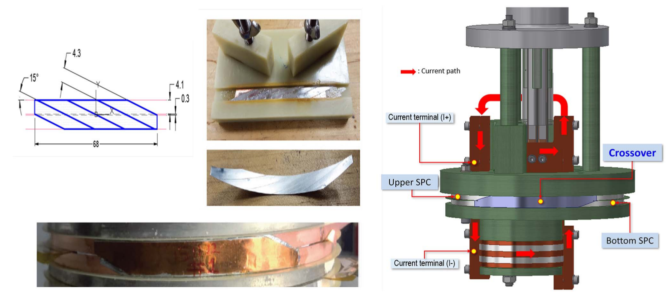

Fig. 1. (a) Crossover joint fabricated using Bi-2223 (Sumitomo Type H) tape conductors, (b) fabricated REBCO SPCs and current path.

II. Experiment Setup

Fig. 1 shows the configuration of the REBCO test coil and crossover joint used in the experiment. Two single pancake coils (SPCs) were fabricated using 10 turns of SP tape each, with 50 µm thick copper tape and 25 µm thick stainless steel tape employed as co-winding materials. In the case of the crossover joint, lab tests repeatedly revealed performance degradation during multiple fatigue cycles due to delamination issues when conventional REBCO tape was used. This degradation was attributed to the high electromagnetic forces induced by the screening current field (SCF) in the REBCO tape, which accelerated mechanical deformation in the crossover joint structure. To mitigate this issue, Bi-2223 tape, which generates less SCF and is structurally more stable, was considered as an alternative to REBCO tape.

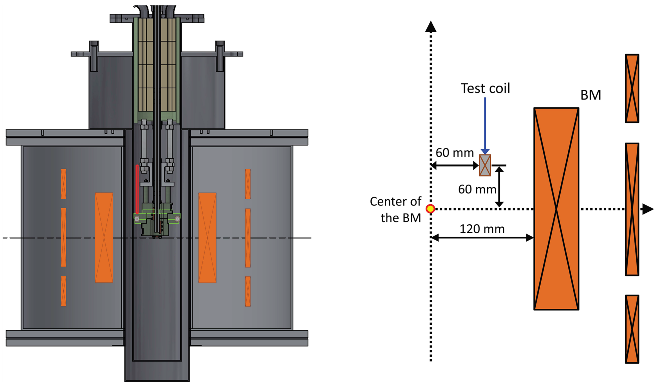

Fig. 2. Schematic diagram of the test coil inside the BM.

TABLE I
SEQUENCE OF TEST EVENTS

seq	Day	Cycle start	Cycle finish	Task
1	1	Charge background, charge insert		
2		0	4154	Cycle from 110-220 A
3		4155	8001	Cycle from 110-220 A
4		8002	12007	Cycle from 110-220 A
5		12008	13004	Cycle from 110-220 A
6	2	13005	20282	Cycle from 110-220 A
7		20283	25025	Cycle from 110-220 A
8		25026	28529	Cycle from 220-420 A
9		28530	34847	Cycle from 300-420 A
10	3	34848	40002	Cycle from 220-420 A
11		40003	50004	Cycle from 300-500 A
12	Post			Ramp to 600 A

As shown in Fig. 1(a), a crossover joint was fabricated using four BI- 2223 tapes and attached to the outermost turns of the two REBCO SPCs, forming a current path from the innermost turn of the upper SPC → outermost turn of the upper SPC → BI- 2223 crossover joint → outermost turn of the bottom SPC → innermost turn of the bottom SPC.

Relevant studies have indicated that in high-field environments, screening current stress (SCS) can generate excessive magnetic stress on REBCO-coated conductors, potentially causing damage if the resulting strain exceeds 0.4%, which corresponds to the strain level retaining approximately 95% of the critical current (I_c) [6], [7]. For the 40 T superconducting magnet currently under design, it is estimated that approximately 0.4% mechanical strain will occur in the REBCO coils and crossover joints due to the SCS. Therefore, as shown in Fig. 2, the test coil was placed inside the 7 T background magnet (BM) and positioned 60 mm in the +Z direction from the center of the BM to induce stress caused by the screening current generated by the vertical magnetic field.

III. Fatigue Operation Test Results

Table I summarizes the operating sequence of the test coil. Inside the 8 T BM magnet, the test coil underwent more than 50000 charge-discharge cycles over a span of three days. It performed approximately 25000 cycles between 110 A and 220 A, 15000 cycles between 200 A and 420 A, and 10000 cycles between 300 A and 500 A, completing a total of 50000 cycles. Fig. 3 shows the results of measuring the voltage and resistance

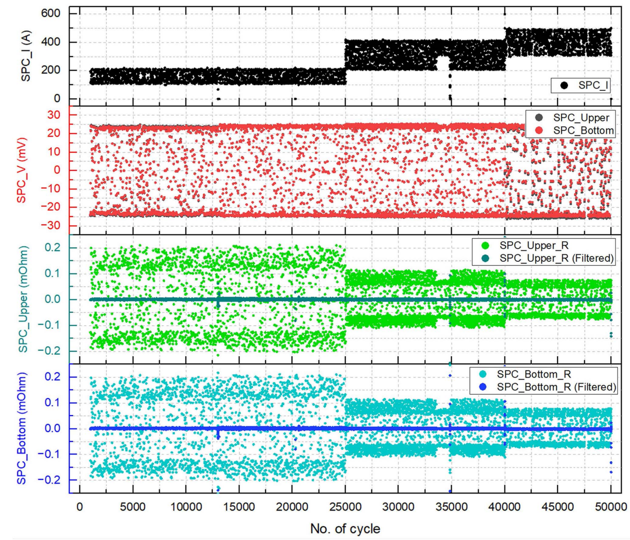

Fig. 3. Fatigue operation results of the test coil: Each graph shows the operating current of each SPC, the voltages (upper and bottom), and the resistance. The resistance data of the SPC disk was filtered using an averaging filter to determine the median value.

of each SPC that constitutes the test coil during the 50000 charge-discharge cycles. The x-axis represents the number of charge-discharge cycles, while the y-axis, from top to bottom, sequentially shows the current of the test coil, the voltage of each SPC, and the resistance. Regarding the voltage of each SPC, it remained consistent between 24 mV and 25 mV throughout the charge-discharge cycles, including the inductance voltage of the coil.

The resistance of each SPC was calculated using the operating current measured by the shunt resistor and the voltage of each SPC. As mentioned earlier, since the voltage of the SPC includes the inductance component, an averaging filter was applied to the calculated resistance values to assess whether the SPC sustained any damage, and these filtered values were also plotted in the graph. If the test coil had been damaged during the 50000 charge-discharge cycles, the filtered resistance of each SPC would have shown a positive or negative slope rather than remaining at zero. However, since the resistance of each SPC remained constant without any slope during the experiment, it can be concluded that the test coil did not sustain any damage throughout the 50000 charge-discharge cycles.

Fig. 4 shows the voltage and resistance components of the crossover joint measured during the 50000 charge-discharge cycles. The resistance of the crossover joint was calculated in the same manner as in Fig. 3, using the operating current measured through the shunt resistor and the voltage of the crossover joint. An averaging filter was applied to confirm the converged resistance values calculated during each cycle. The experimental results show that the resistance of the crossover joint ranged between 25 nΩ and 50 nΩ throughout all cycles, indicating that the crossover joint is also unlikely to have sustained any damage.

IV. Estimation of the Strain on the Crossover by the Floss Simulation

Based on the operating conditions of the test coil, the distribution of mechanical deformation occurring in the test coil at

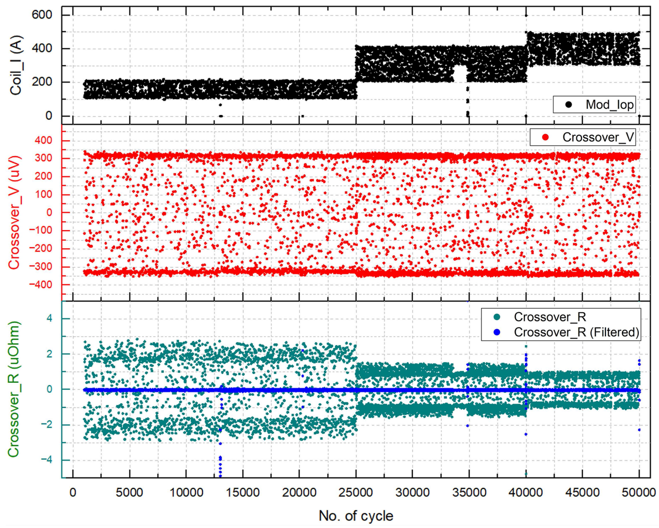

Fig. 4. Fatigue operation results of the crossover joint: Each graph shows the operating current of the test coil, the crossover joint voltage, and the resistance. The resistance data of the crossover was filtered using an averaging filter to determine the median value.

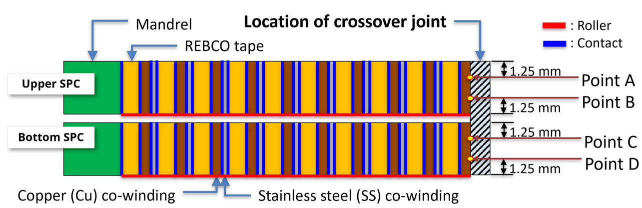

Fig. 5. Geometric shape of the structural model and its boundary conditions for the test coil.

each operating current was estimated through FEM simulations. Fig. 5 shows the detailed structure of the test coil used in the simulation. The test coil consists of 10 turns of REBCO tape wound on a G10 mandrel, with copper tape and stainless steel tape co-wound between the REBCO turns. Boundary conditions include contact conditions between all tape layers and roller conditions at the bottom of each SPC. The contact condition refers to the interface between different materials (REBCO tape, copper tape, and stainless steel tape), modeled as frictionless contact. This condition was applied to the radial (r-direction) contact surfaces between the materials. The roller condition was applied to the bottom surfaces of each material, constraining displacement in the z-axis direction to zero. To clearly indicate where the roller and contact conditions are applied, the corresponding regions are highlighted in Fig. 5 with a thick red line (roller condition) and a blue line (contact condition).

Table II presents the detailed parameters of the test coil's dimensions and the mechanical properties of the materials used in the simulation. The equivalent Young's modulus and Poisson's ratio for the materials composing the test coil were calculated considering the 4.2 K experimental conditions and the anisotropic structure of the coil.

To estimate the critical current distribution inside the test coil, the Sin^2 function (1)–(4) shown below was used.

$$I_c\ (B,\theta) = \frac{a\,(B) - c\,(B)}{1 + \omega^2\,(B)\,sin^2\,(\theta)} + c\,(B) \tag{1}$$

TABLE II
KEY PARAMETERS FOR THE FLOSS STRUCTURE ANAYSIS

Item	Unit	Value
REBCO Coil Parameters		
I.R. of the test coil	[mm]	60
REBCO tape thick.	[mm]	0.1
Co-winding (Cu) thick.	[mm]	50.8
Co-winding (SS) think.	[μm]	25.0
Winding turns	[turns]	10
Over-band (SS) turns	[mm]	2
Mandrel thickness	[mm]	28.175
Central B_z of the BM	[T]	8
Conductor Parameters		
REBCO E [R, Θ, Z]	[GPa]	104.7, 143.0, 142.1
REBCO ν [RΘ, ΘZ, RZ]		0.321, 0.322, 0.321
REBCO G [RΘ, ΘZ, RZ]		39.8, 54.8, 39.7
REBCO α (293 K - 4 K) [R, Θ, Z]	[1/K]	9.79e-6, 8.77e-6, 8.78e-6
Copper E (4.2 K)	[GPa]	55
Copper ν (4.2 K)		0.34
Copper α (293 K – 4 K)	[1/K]	-1.13e-5
Stainless steel E (4.2 K)	[GPa]	165
Stainless steel ν (4.2 K)		0.282
Stainless steel α (293 K – 4 K)	[a/K]	1.03e-5
G10 E [R, Θ, Z]	[GPa]	22.0, 33.5, 33.5
G10 ν [RΘ, ΘZ, RZ]		0.211, 0.211, 0.211
G10 G [RΘ, ΘZ, RZ]	[GPa]	13.9, 9.1, 13.9
G10 α [R, Θ, Z]	[1/K]	24.4e-6, 8.34e-6, 8.34e-6

TABLE III
PARAMETERS FOR THE CRITICAL CURRENT CALCULATION

Item	Value
a_1	1919.9
a_2	37.221
ω_1	3.6474
ω_2	0.32003
c_1	1402.5
c_2	0814532
ab-plane offset	2.9°

$$a\ (B) = a_1\ \exp\left(-\frac{B}{a_2}\right) \tag{2}$$

$$c\ (B) = c_1\ B^{-c2} \tag{3}$$

$$\omega\ (B) = \omega_1\ B^{\omega 2} \tag{4}$$

In this equation, "B" and "Theta" represent the magnitude and angle of the external magnetic field applied to the ab-plane of the REBCO tape, while Table III provides the parameters used in the Sin^2 function. Using these parameters and the FLOSS model developed by NHMFL [8], [9], the hoop strain distribution inside the test coil, considering the SCF, was estimated.

Fig. 6 shows the distribution of the critical current ratio and hoop strain according to the operating current of the test coil. Fig. 7 presents the simulated hoop strain values at four measurement points located inward (center between the SPC core and bottom side) and outward (center between the SPC core and upper side) of each SPC, depending on the operating current of the test coil. The simulation results confirmed that

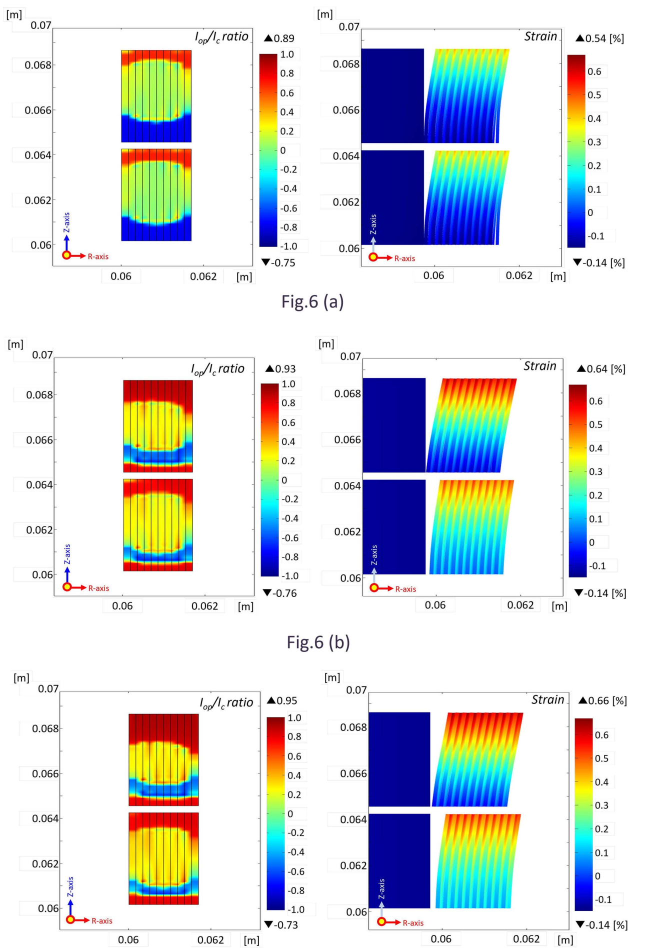

Fig. 6. Critical current ratio (L) and strain (R) distribution of the test coil: (a) at 220 A, (b) at 420 A, (c) at 500 A.

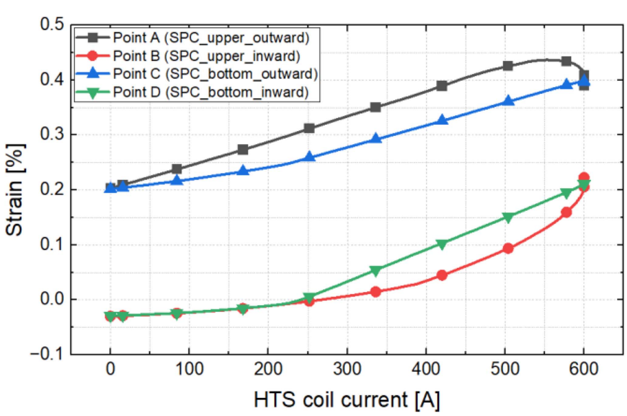

Fig. 7. Strain variation at the measurement point (in Fig. 5) during the test coil charging.

an uneven critical current distribution occurred across the cross sectional area of the SPC due to the SCF. Similarly, the hoop strain distribution at the top and bottom of the SPC exhibited an uneven pattern.

The simulation indicated that at an operating current of 220 A, a peak hoop strain ranging from 0.54% to −0.14% occurred in the test coil. At the four measurement points shown in Fig. 5, hoop strain values of 0.3% (point A), 0.25% (point C), and -0.007% (points B and D) were observed. When the operating current was increased to 420 A, the simulation revealed the test coil's peak hoop strain values of 0.64% and −0.14%, and hoop strain values of 0.39% (point A), 0.33% (point C), 0.1% (point B), and 0.04% (point D) were observed at the four measurement points. Unlike the conditions at 220 A, all points exhibited extended hoop strain. Under the 500 A operating current condition, hoop strain values of 0.42% (point A), 0.36% (point C), 0.15% (point B), and 0.09% (point D) were simulated. Based on the simulation results, it is estimated that the target hoop strain of 0.4% was achieved at all operating current conditions of the test coil. Additionally, considering that the actual test coil did not sustain any damage during fatigue operation, it is concluded that the suggested REBCO coil structure and the crossover joint made from BI-2223 can withstand 50000 charge-discharge cycles in an environment where hoop strain levels around 0.4% are generated.

V. Conclusion

This study investigated the fatigue properties of a REBCO coil using copper tape and stainless steel tape as co-winding materials, along with a crossover joint made from Bi-2223 tape, through experiments and FEM simulations. The results demonstrated that the proposed test coil configuration can withstand the target 50000 charge-discharge cycles under conditions generating approximately 0.4% hoop strain. Notably, the crossover joint did not exhibit the delamination issues observed in crossover joints made from REBCO tape, suggesting that Bi-2223 tape could be a suitable replacement for REBCO tape in future crossover joint fabrication.

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