Investigation of Electromechanical Properties in REBCO Coated Conductor Tapes by High-Cycle Fatigue Test at 77K

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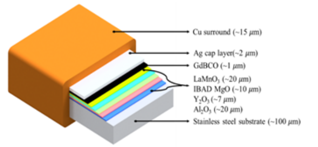
Introduction

- In the second generation (2G) (RE)$Ba_2Cu_3O_{7-x}$ high-temperature superconducting (HTS) applications, various fatigue loading conditions such as periodic electromagnetic force are certain. In real applications, fatigue behaviors of REBCO CC tapes will critically affect the long-term reliability of superconducting performance if not fully address. The evaluation of the characteristics of CC tapes under operating stress/strain is an important procedure to determine the current carrying capacity, its performance, and the reliability of the device.
- Recent achievement of the critical current (I_c) of 1 kA/cm widened the application of 12 mm width CC tapes. It showed a different characteristic as compared with the conventional 4 mm width ones. Therefore, it is important to evaluate the mechanical and electro-mechanical properties of both 4 and12 mm width CC tapes under fatigue loading.
- In this work, the I_c degradation behaviors of 4-mm and 12-mm wide IBAD/RCE-DR Cu-stabilized GdBCO CC tapes using high cycle fatigue test were investigated at 77K and at a stress ratio, R = 0.1. Mechanical and electromechanical fatigue limits of CC tapes were determined. The mechanical fatigue limit of CC tapes was derived from *S-N* curve at 77K. The electrical fatigue limit was determined based on I_c-repeated cycle, *N*, relations.
- In addition, the micrographs and fractographs of as-received and fatigue tested (at 77K) specimens were observed under OM, SEM-EDS and EPMA, respectively, to clarify the influence of CC tapes architecture and the applied maximum stress level (σ_{max}) on the mechanical and electromechanical fatigue behaviors.

Experimental procedure

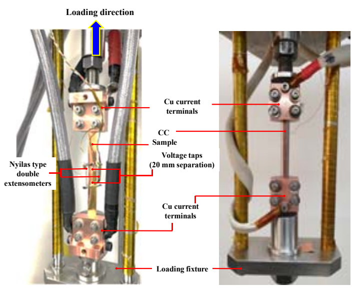
Sample specifications



Specification of CC samples		
Fabrication process	IBAD/GdBCO CC RCE-DR	
Structure	Ag/GdBCO/$LaMnO_3$/ Homo-epi MgO/IBAD MgO/ Y_2O_3/AlO_3/Stainless steel/Cu stabilized	
GdBCO film (*t*)	~ 1 µm	
Substrate, (*t*)	Stainless steel, ~100 µm	
Stabilizer, (*t*)	Cu surround, ~15 µm	
Dimension, t x w (*mm*)	0.134 mm x 12.05 mm	0.130 mm x 4.05 mm
Critical current (I_c)	~ 850 A	~230 A
Manufacturer	SuNAM	

- Slit edge parts on the 4-mm width CC tapes were observed at cross-section
- Images of EPMA: deformations of STS substrate on the edge of the tape, resembling a burr like structure in the case of 4-mm CC tape
- The adopted CC tape's fabrication processes (slitted or non-slitted) were considered and linked to the electromechanical fatigue behaviors

Set-up for I_c measurement during uniaxial tension and fatigue tests



Electromechanical property evaluation under fatigue loading

- Fatigue test: I_c and n-value were measured at specified number of cycles continuously at 77 K using a single specimen
- Voltage taps separation of 20 mm
- I_c was measured using the four-probe method with an electron field criterion of 1 µV/cm

Uniaxial tension test

- Shimadzu universal testing machine: load cell capacity of 5 kN.
- 25mm Nyilas-type double extensometer: record displacement
- CC tapes were held by Cu terminal blocks at both ends
- Continuous loading
- Displacement control: 1 mm/min
- Sample length:
  Total length = 120 mm
  Gage part length = 60 mm

Fatigue test conditions

- Constant stress amplitude
- Frequency: 10 Hz
- Applied maximum stress (σ_{max}) levels: determined based on σ_y
- Stress ratio, R = 0.1

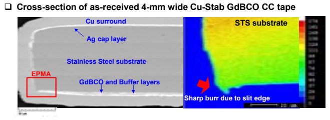
Fatigue parameters for loading

$$\text{Stress ratio, } R = \frac{\sigma_{min}}{\sigma_{max}}$$

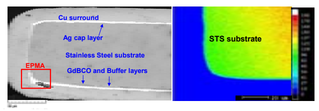
$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2}$$

Cross-sectional views

- Cross-section of as-received 4-mm wide Cu-Stab GdBCO CC tape



- Cross-section of as-received 12-mm wide Cu-Stab GdBCO CC tape

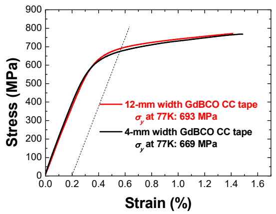


Micrograph and fractographic observations

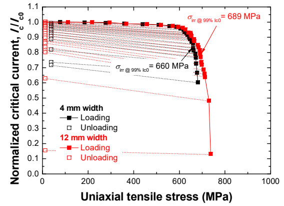
- Samples before and after fatigue tests were observed at the surfaces and cross-sections microscopically through SEM-EDS and EPMA
- etching process for cross-sections observations:
  - To remove the Ag layer: 25% vol H_2O_2 + 25% vol NH_4OH + 50% vol H_2O
  - To remove the Cu layer: 30% vol HNO_3 + 70% vol H_2O

Results and Discussion

Uniaxial tensile loading

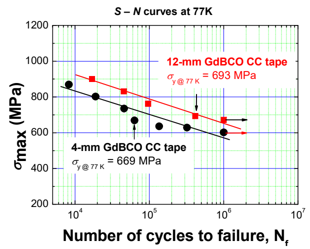


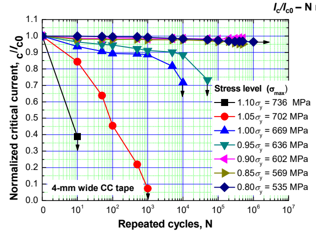
Stress-strain curves
Yield stress, σ_y

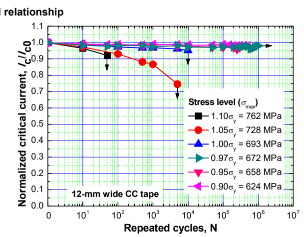


Irreversible Stress limit (σ_{irr}) for the onset of I_c degradation, *99% I_{c0} recovery criterion*

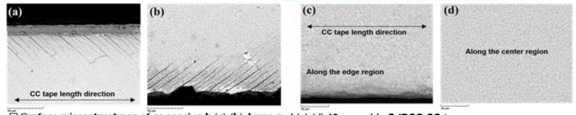
Fatigue loading



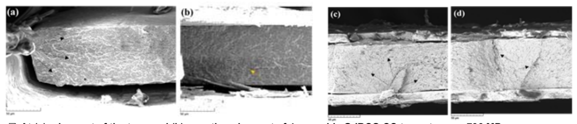




Micrographic and fractographic observations



- Surface microstructures of as-received: (a)-(b) 4-mm and (c)-(d) 12-mm wide GdBCO CC tapes
- Fatigue cracks' initiation locations and appearances are attributed to the CC tape architecture



- At (a) edge part of the tape and (b) near the edge part of 4-mm wide GdBCO CC tape at σ_{max} = 736 MPa
- At the middle regions of the tape (c) and (d) of 12-mm wide GdBCO CC tape when σ_{max} = 762 MPa

Comparison of properties at 77 K

	Uniaxial tension stress		Fatigue stress limits	
RCE-DR GdBCO	Yield Stress (σ_y), MPa *(0.2% offset strain)*	Irreversible Stress Limit (σ_{irr}), MPa *(99% I_{c0} recovery criterion)*	Mechanical Fatigue Stress Limit (σ_{Mech}), Mpa *(at 10^6 cycles)*	Electrical Fatigue Stress Limit (σ_{Elec}), Mpa *(at 10^6 cycles)*
4-mm wide	669	660	609	602
12-mm wide	693	689	679	672

- Electrical and mechanical fatigue stress limits: stress level in which the sample did not fail up to 10^6 cycles electrically (no I_c degradation) and mechanically, while electrical fatigue strength (I_c degraded below the 95% I_c retention line) and mechanical fatigue strength (stress where the failure occurs)
- 4-mm wide sample produced a bit lower fatigue limit as compared with the 12-mm wide one, electrically and mechanically
- Electrical fatigue limit of the CC tape depends on the fracture behavior of the SC layer, on the other hand, substrate layer dominantly influenced the mechanical fatigue performance

Conclusions

- Through high cycle fatigue tests at R = 0.1 and at 77K, electromechanical fatigue performances of 4-mm wide and 12-mm wide GdBCO CC tapes were investigated.
- Influence of the tape width existed. Damages developed through CC tape slitting created a stress concentration, large enough to cause crack initiation on the SC layer which consequently resulted in I_c degradation. The 4-mm wide CC tape sample produced a bit lower fatigue limit as compared with the 12-mm wide one.
- The 12-mm wide CC samples showed a superior fatigue strength compared to the 4-mm wide one, especially mechanically, The microcracks observed in the edges of as-received 4-mm wide CC samples propagated into the width direction of the CC tape as the applied stress level increases, causing SC and buffer layers damages such as delamination.
- Through the fractographic observations, it can be found that the electrical fatigue limit of the CC tape depends on the fracture behavior of the SC layer, while the substrate layer dominantly influenced the mechanical fatigue strength.

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