Fatigue Properties of IBAD-MOCVD REBa$_2$Cu$_3$O$_{7-x}$

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Introduction

• High current, high field magnets experience stresses during fabrication, cool-down, and operation
• REBCO tapes show promise in many devices, many of these operate in AC mode
• Previous studies have related stress/strain to $I_c$ reduction over a single cycle
  – Barth et al. (SUST Vol.28, 2015) showed that the irreversibility limit of different REBCO conductors ranges from $\varepsilon=0.45-0.7\%$
• Fatigue damage is possible at lower strain values than irreversibility limit as shown by Mbaruku et al. (TASC Vol.18, 2008) using SuperPower tapes
  – Above $\varepsilon=0.4\%$ and 10,000 cycles, $R=.2$, critical current degrades
• Many variables exist within REBCO tapes
• Limited fatigue information is available
  – Must be well understood for magnet design
Fatigue Overview

- R value=$\epsilon_{\text{min}}/\epsilon_{\text{max}}$
  - For fully reversed loading R=-1
  - For fully relaxed loading R=0
- Composite material such as REBCO requires parameters to define failure
- Failure must be defined electrically, not mechanically
  - Failure will be defined as a 10% reduction in $I_c$
Experimental Approach

- Samples were from the same batch produced by SuperPower and SuNAM, and replaced after each set of cycles, IE: no sample was mounted twice for fatigue testing
- Fatigue performed at room temperature (22° C) with $\varepsilon = 0.35\%, 0.45\%, \text{ and } 0.50\%$ for up to 100,000 cycles; $R=0$
- $I_c$ measured at 77 K self-field, four point method both before and after fatigue; $I_c(\varepsilon)/I_{c0}$ vs. cycles was plotted to show degradation of conductor
- Etching for microscopy was performed after $I_c$ measurements
$I_c(\varepsilon)/I_{c0}$ vs. cycles, SuNAM and SuperPower

- 0.35% SuNAM
- 0.35% SP
- 0.45% SuNAM
- 0.45% SP
- 0.5% SuNAM
- 0.5% SP

n-value vs. cycles, SuperPower YBCO
n-value vs. cycles, SuNAM GdBCO

[Graph showing critical current index value (n) against number of cycles for different strain values (ε = 0.35%, ε = 0.45%, ε = 0.50%).]
SuperPower SEM

As-received tape:

- Cracks are observed along the edge
- Their spacing varies from 5 to 30 μm
- The cracks are typically ~ 65 μm in length.

0.45% for 1000 cycles:

- Similar edge cracking, no \( l_c \) reduction, Reduction in n-value
- \( l_c(\epsilon)/l_{c0} = 1.0 \)
- Arrow indicates load direction

SuperPower, 0.45% for 1000 cycles, $I_c(\varepsilon)/I_{c0} = 1.0$

- Multiple craters are visible in both as-received and fatigued tapes
  - Range in size from 30µm to 300µm
  - Notice microcracking radiating from the defects
  - n-value much lower in fatigued sample vs. as-received tape

Delamination most often occurs in buffer stack for both craters and cracked surface.

Important to note area of failure to improve mechanical properties.
Superpower 0.45% strain; 10,000 cycles, $I_c(\varepsilon)/I_{c0} = 0.96$

- Delamination has occurred at the edge of tape where microcracks originated
- EDS confirmed YBCO layer has delaminated, exposing buffer stack
- Crack propagation from the conductor edge inwards at $\sim 41^\circ$
- Crater defects are visible and have cracks ranging in length from 10- 45 mm
SuNAM SEM

As-received
- Notice faint cracks, similar slitting damage to SuperPower tape
- 25 degree angle inward
- 10-20 µm average length

1000 cycles @ 0.5% ; 0.91 I/I_c
- Etching damage seen
- Can still see the ends of the edge cracks
- Cracks end ~80-100 µm from edge of tape
Conclusions

• SuperPower retained $I_c$ up to $\varepsilon=0.35\%$ and $\varepsilon=0.45\%$ at 10,000 cycles, and $\varepsilon=0.5\%$ at 100 cycles
• SuNAM retained $I_c$ up to $\varepsilon=0.35\%$ and $\varepsilon=0.45\%$ at 10,000 cycles, and $\varepsilon=0.5\%$ at 1000 cycles
• Manufacturing defects leading to crack propagation $\rightarrow$ main reasons for failure
  – Slitting process
  – Deposition defects “craters”
• Failure/delamination occurs at the buffer stack in REBCO tapes that have been studied
• At high $\varepsilon$ and low $N$, we find greater fatigue life than Mbaruku et al.; whereas at low $\varepsilon$ and high $N$ the fatigue life is shortened due to greater total strain energy