Fermilab

March 25th, 2026

Effects of Stabilizer Strength on the Delamination Resistance of REBCO Coated Conductors

Fang Wan and Xingchen Xu

U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

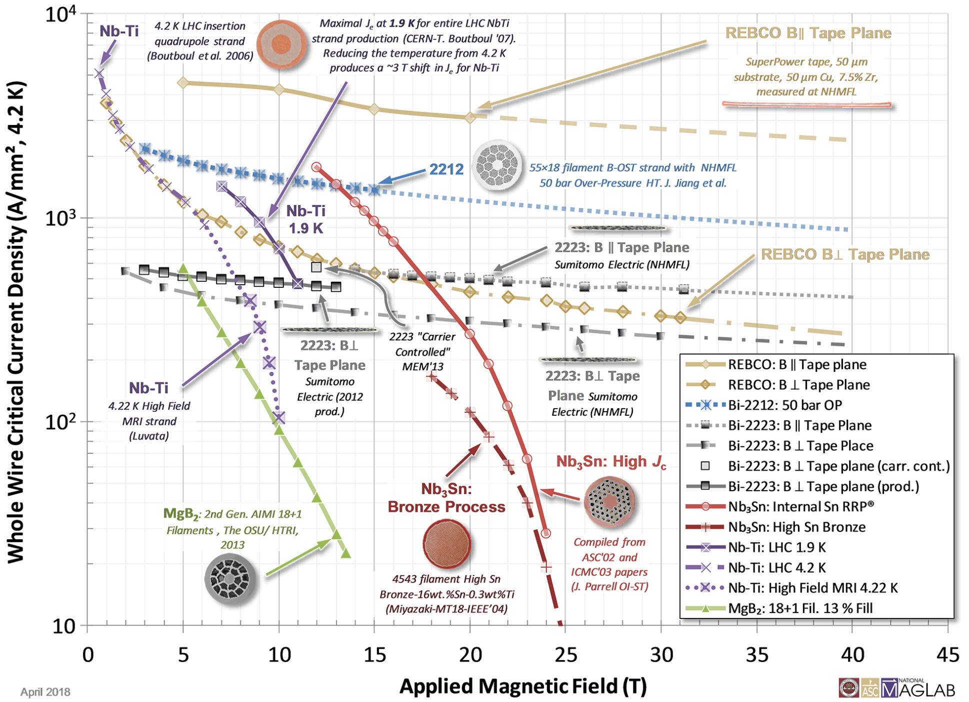
FERMI NATIONAL ACCELERATOR LABORATORY

01

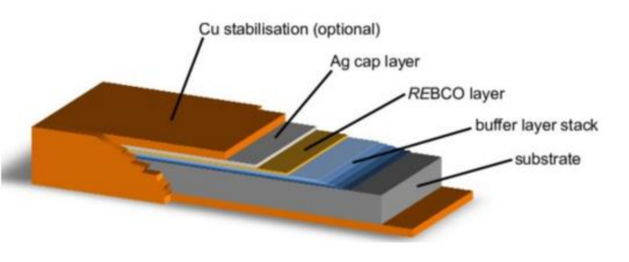
Motivation

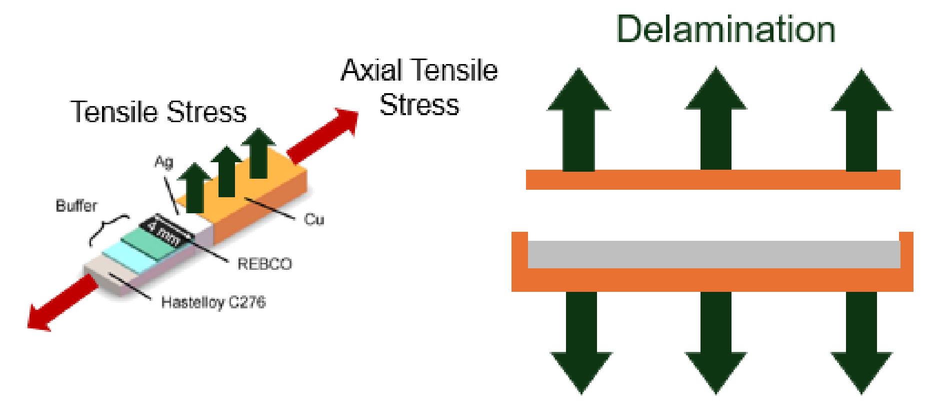
Motivation

Material	T_c (K)	Practical Field and Temperature	Price per Liter ($)
MgB_2	~ 39	3 – 7 T, 10 – 20 K	1 x 10^3
NbTi	~ 9	8 – 10 T, 1.9 – 4.2 K	2 x 10^3
Nb_3Sn	~ 18	10 – 16 T, 1.9 – 4.2 K	1.5 x 10^4
REBCO	~ 92	> 20 T, 20 K	1 x 10^5
Bi-2212	~ 85	> 20 T, 20 K	1 x 10^5



- Key Challenge: Mechanical Reliability of REBCO Conductors in Ultra-High-Field Magnets.





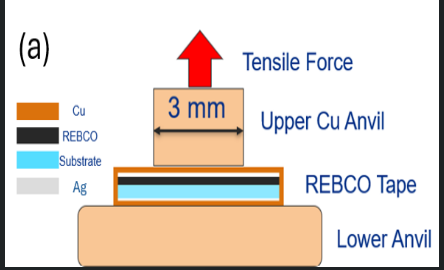
- Tensile strength along longitudinal axial direction: 500 – 700 MPa,
- Tensile strength along transverse direction: **2 – 100 MPa**.
- Delamination failure was caused by **transverse tensile stress**, causing irreversible critical current degradation.

02

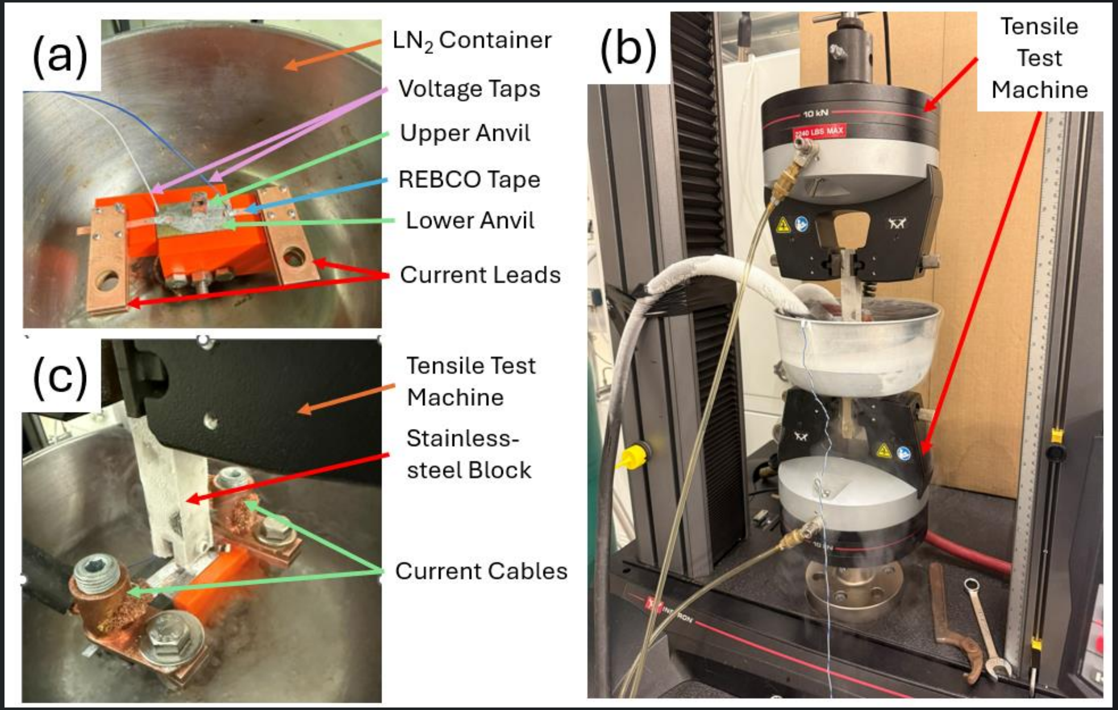
Electromechanical Delamination Testing

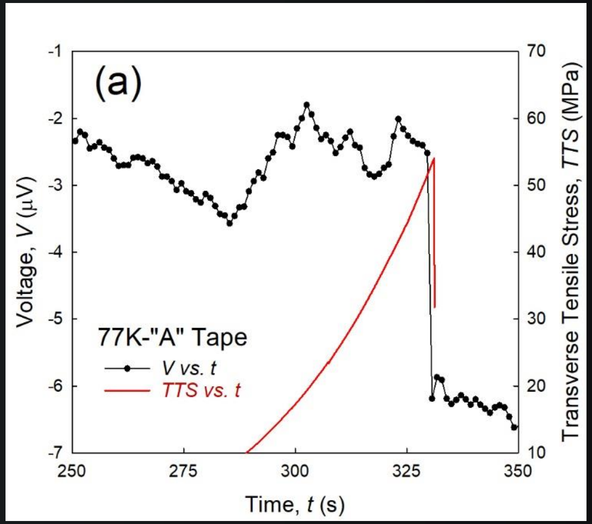
Electromechanical Delamination Testing

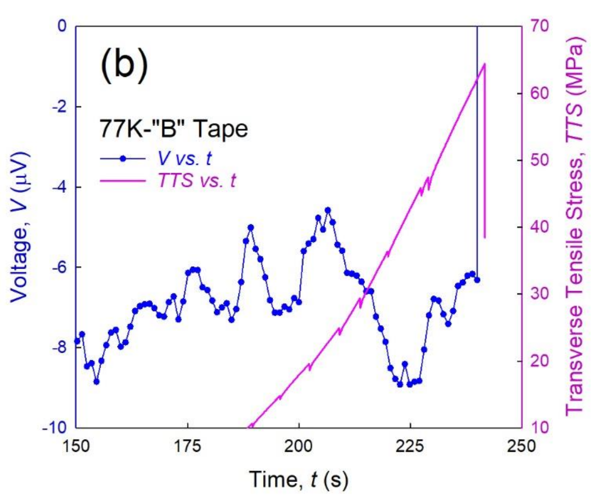
Purpose: Build a relationship between I_c degradation and delamination strength for ReBCO tape.



- Test critical current I_c without applied force at 77 K
- Input transport current equal to 99% of I_c at 77 K and maintain constant current
- Applied increasing tensile force at a constant displacement of 0.5 mm/min
- Test continues until mechanical delamination occurred







Parameter	"A"	"B"
$I_{c,77K}$	178	151
$I_{applied}/I_c$	0.983	0.987
Quench Time (s)	330.69	239.98
Delamination Time (s)	331.15	241.68
DS (MPa)	54.1	64.4

- Delamination and quench approximately occurred at the same time
- Prior to delamination, I_c degradation ≤ 1.0%.
- After delamination, REBCO tape was completely fractured, leading to the quench.

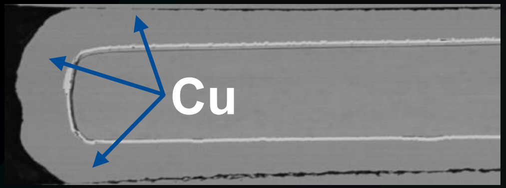
03

Influence of Stabilizer Strength on Delamination Resistance

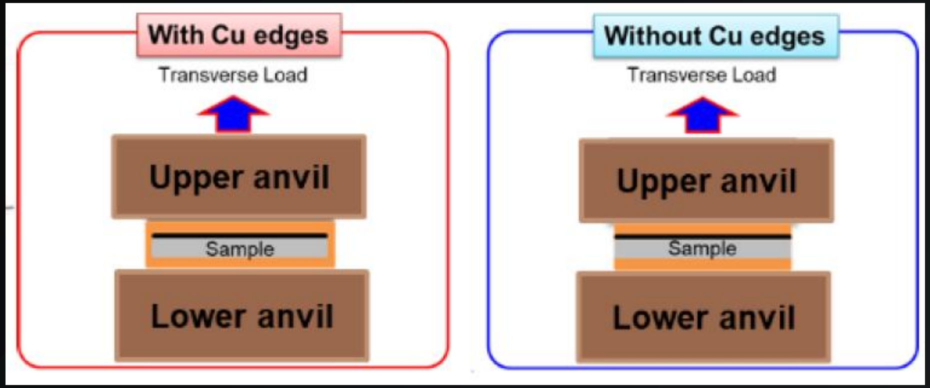
Influence of Stabilizer Strength on Delamination Resistance

Hypothesis: *Enhancing delamination resistance by improving the mechanical strength of stabilizer*

Cu-electroplated ReBCO tape

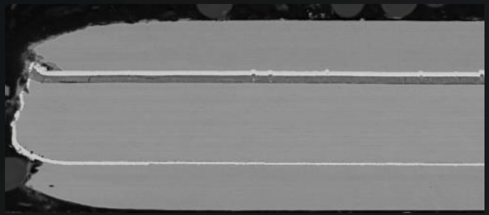


DS of ReBCO=
Stabilizer Contribution to Delamination Resistance
+
Interfacial bonding strength among multiple layers



De Leon. M et al. *IEEE Trans. Supercond. Technol.*
REBCO tape without edges (n.E.): The applied tensile load is only supported by the interlayer bonding

Delamination resistance contributed by stabilizer, Δ*DS*:
DS of REBCO with Cu edges – *DS* of REBCO without Cu edges
DS (w.E.) *DS* (n.E.)

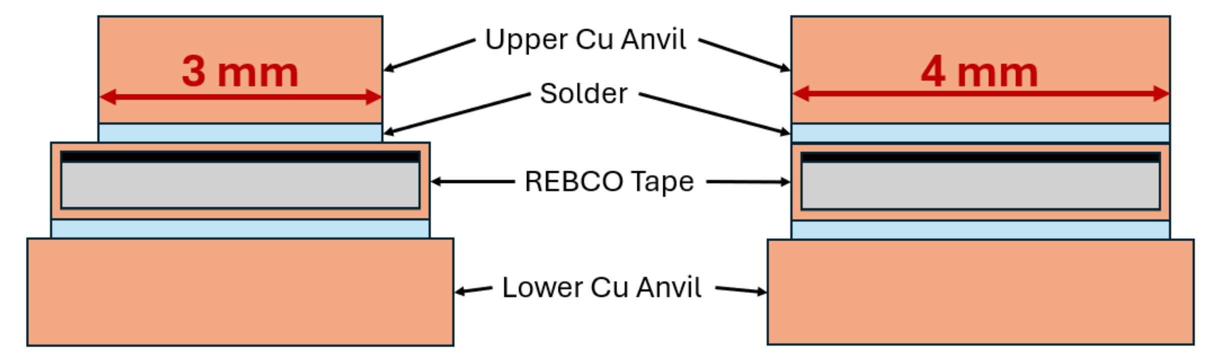


This study: Remove stabilizer edges by copper etching

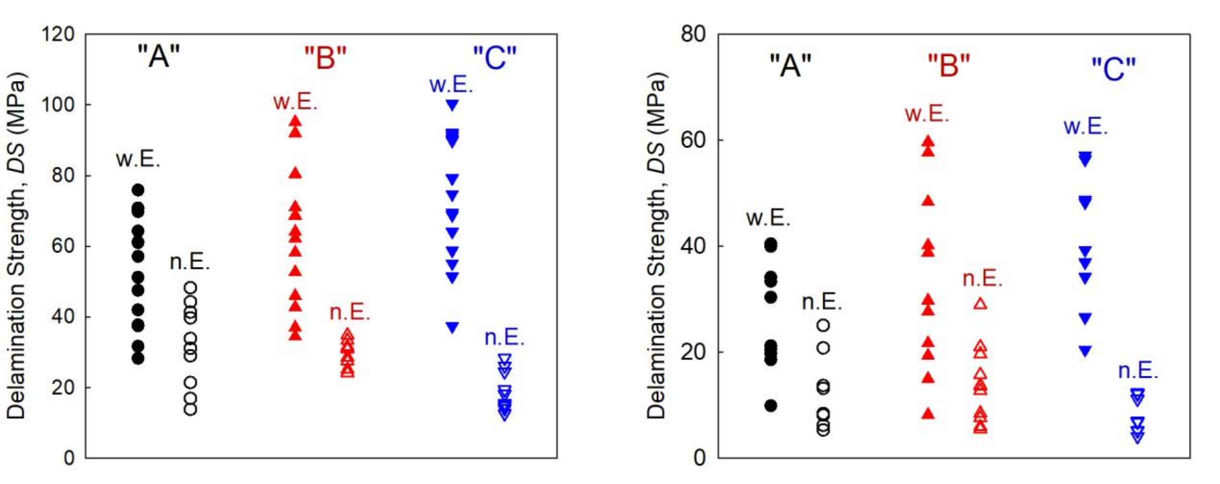
Sample	"A"	"B"	"C"
Thickness of Stabilizer Edge (μm)	21.9 ± 0.2	18.6 ± 0.3	21.9 ± 0.1

Steps:

- Test *DS* (w.E.) and *DS* (n.E.) at RT
- Quantify the stabilizer contribution to delamination resistance Δ*DS* = *DS* (w.E.) – *DS* (n.E.)
- Measure the mechanical strength of stabilizer edges



Influence of Stabilizer Strength on Delamination Resistance



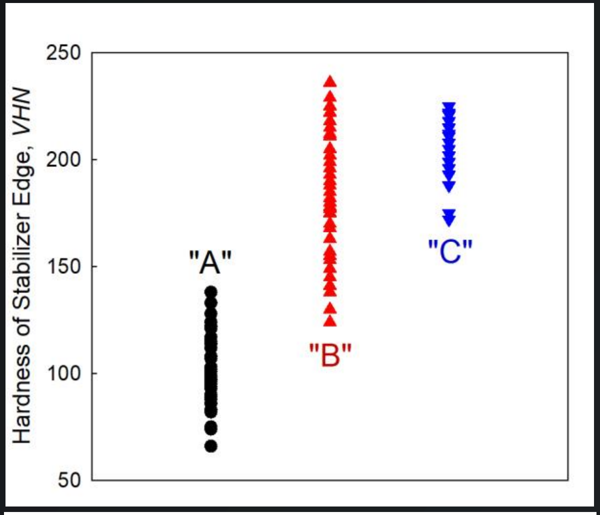
3-mm Anvil

4-mm Anvil

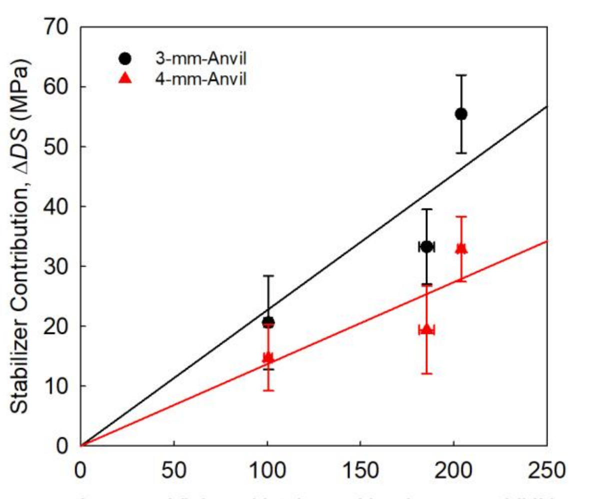
Sample	*ΔDS*, 3-mm-Anvil (MPa)	*ΔDS*, 4-mm-Anvil (MPa)
“A”	20.6 ± 7.8	14.7 ± 5.5
“B”	33.3 ± 6.3	19.4 ± 7.3
“C”	55.5 ± 7.8	32.9 ± 5.4

Vickers Hardness Number (*VHN*) = proxy of mechanical strengths of stabilizer

Copper alloys:
*Yield Strength (YS) = 2.87 * VHN*
*Ultimate Tensile Strength (UTS) = 3.35 * VHN*



- *HVN* of “A” tapes is the lowest
- 90% of *HVN* values for “C” sample’s stabilizer ≥190, but 46% of *HVN* values for “B” sample’s stabilizer ≥ 190.
- Mean *HVN* of “C” is higher than that of “B”.

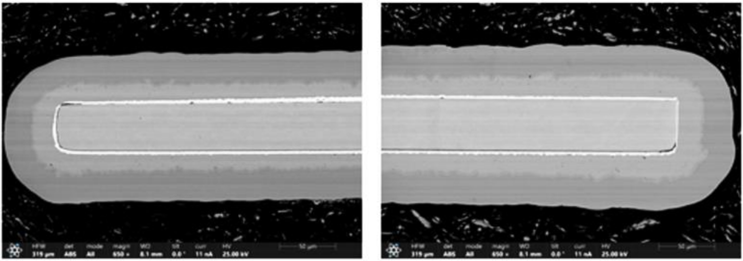


- Delamination Resistance contributed from Stabilizer (*ΔDS*) versus Vickers Hardness Number (*VHN*) of Stabilizer Edge
- As *VHN* increases from **100 to 200**, *ΔDS* increase by **18 – 35 MPa at RT**

Influence of Stabilizer Strength on Delamination Resistance

Strategy to improve delamination resistance:

Deposit high-strength Ni-P layer onto REBCO tape



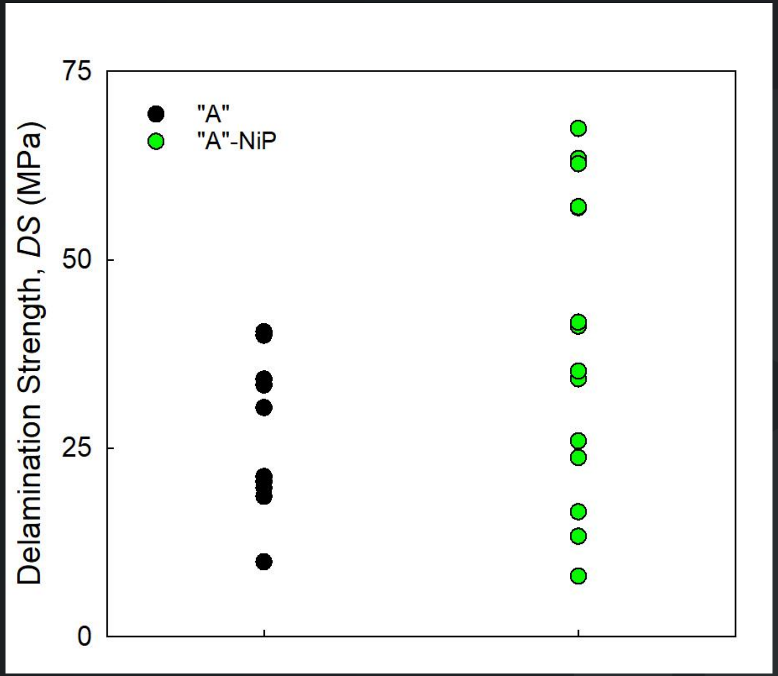
VHN:

- Ni-P: 300 – 600
- Cu: 100 – 200

Linear Correlation: $\Delta DS = 0.137\ HVN$

- Mean *HVN* of Ni – P layer: 500
- Estimated ΔDS (Ni-P) = 69 MPa

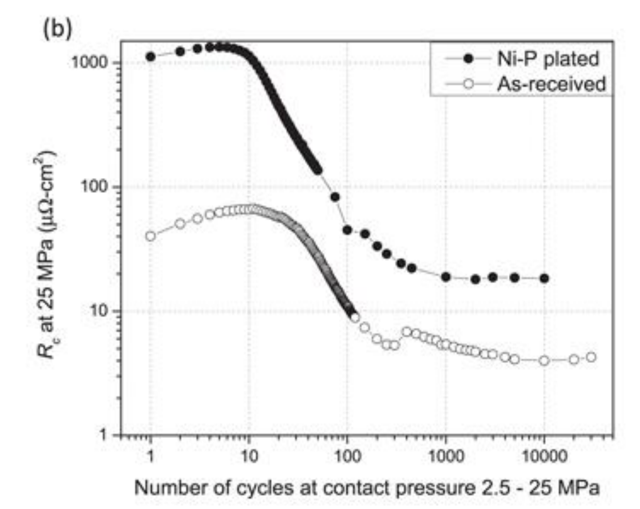
	Mean DS, (MPa)	*Max. DS* (MPa)
"A"	26.8 ± 3.2	40.4
"A"-NiP	39.3 ±5.0	67.4
ΔDS	12.5 ± 8.2	27.0



Another Advantage:

High Turn-to-Turn Resistivity, R_c

- 20 μm Ni – P plated layer ≈ 14,000 μΩ/cm^2
- Suitable R_c = 1,000 to 100,000 μΩ/cm^2



Drawback:

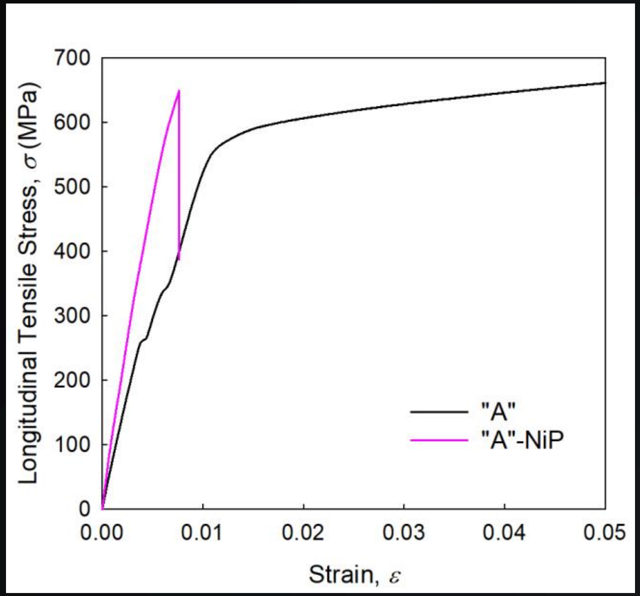
Sensitive to load cycling.

Jun Lu et al 2018 *Supercond. Sci. Technol.* **31** 085006

Influence of Stabilizer Strength on Delamination Resistance

Influence of Stabilizer Ductility:

Ni – P coating layer is brittle and highly susceptible to catastrophic, early failure under tensile loads



If high-strength materials are used to replace Cu as the REBCO stabilizer:

it is essential to consider their toughness, i.e., the ability to combine high strength with sufficient ductility.

Future Directions

Develop High-delamination-Resistance REBCO tape:

- Optimize the copper electroplating process to increase mechanical strengths of Cu stabilizer
  - Bath chemistry and temperature
  - Current density and mode (pulse)
  - Agitation condition
- Introduce high-strength materials into REBCO stabilizer.
  - Achieve a balance among mechanical strength, ductility, and resistivity.
- Increase interfacial bonding strength between REBCO layer and buffer stacks

Summary and Acknowledgement

Build an electromechanical testing system to evaluate I_c degradation of REBCO tape under transverse tensile stress at 77 K.

Establish an effective strategy to enhance the delamination strength of REBCO tapes

I appreciate the technical support provided by my Fermilab colleagues (Daniele Turrioni, Steven Krave, and Maria Baldini)."

Fermilab

FermiFORWARD

U.S. DEPARTMENT of ENERGY

FERMI NATIONAL ACCELERATOR LABORATORY