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Irreversible Tensile Stress of 2G HTS Wires made by IBAD-MOCVD on Hastelloy Substrates

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SuperPower Inc. is a subsidiary of Furukawa Electric Co. Ltd.

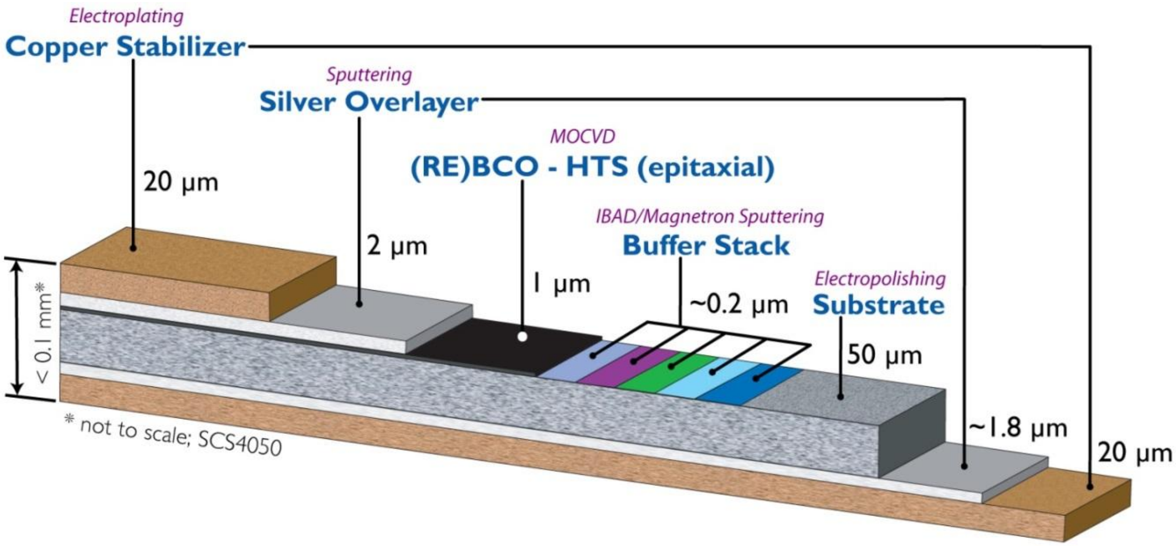
M2OrB-02

Outline

- 2G HTS wire production at SuperPower
- Mechanical and electromechanical (MEM) testing at SuperPower
- Measurements done in this work
- Stress-strain relationships at 77K under uniaxial tension
- Critical stress/strain and irreversible stress/strain at 77K under uniaxial tension
- Effects of Cu stabilizer thickness on MEM properties
- Summary

2G HTS wire production at SuperPower

REBCO wire produced by IBAD-MOCVD on Hastelloy substrate



- REBCO formulation:
  - **AP** (Advanced Pinning) – with enhanced in-field performance for B//c, targeting at coil applications such as high-field magnets, SMES, motors/generators
  - **CF** (Cable Formulation) – for cables, transformers, resistive type SFCL
- I_c(77K, s.f.)/12mm=300-600A, piece length=300-500m
- Variations in width (2-12mm), substrate thickness (30, 50 or 100μm), Ag thickness (1-5μm), total Cu thickness (10-115μm), and insulation
- Product lineup is expanding

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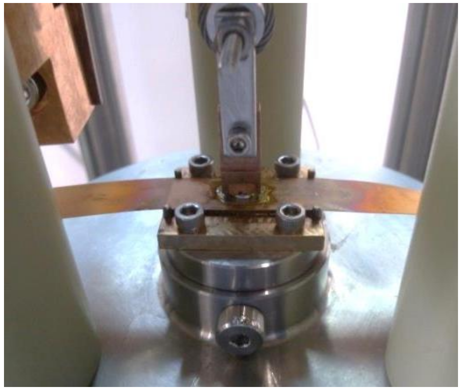
Mechanical and Electromechanical (MEM) testing

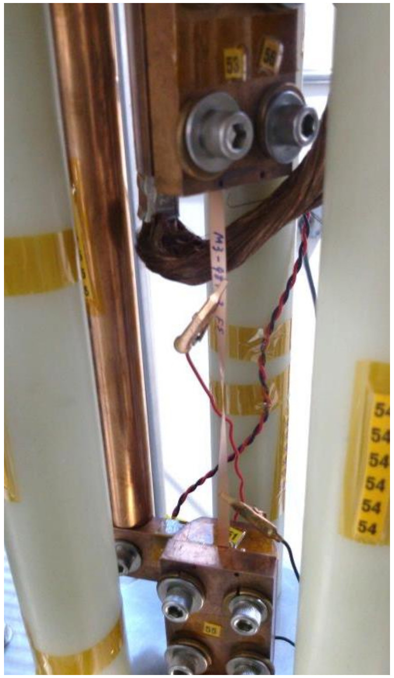
at SuperPower

- System built on a Shimadzu universal tester (switching between different testing modes)
- Electromechanical testing (I_c measurement under loading) at 77K in LN2
- Serves for QC and R&D



Transverse tension

Uniaxial tension



Torsion + axial tension

Transverse compression

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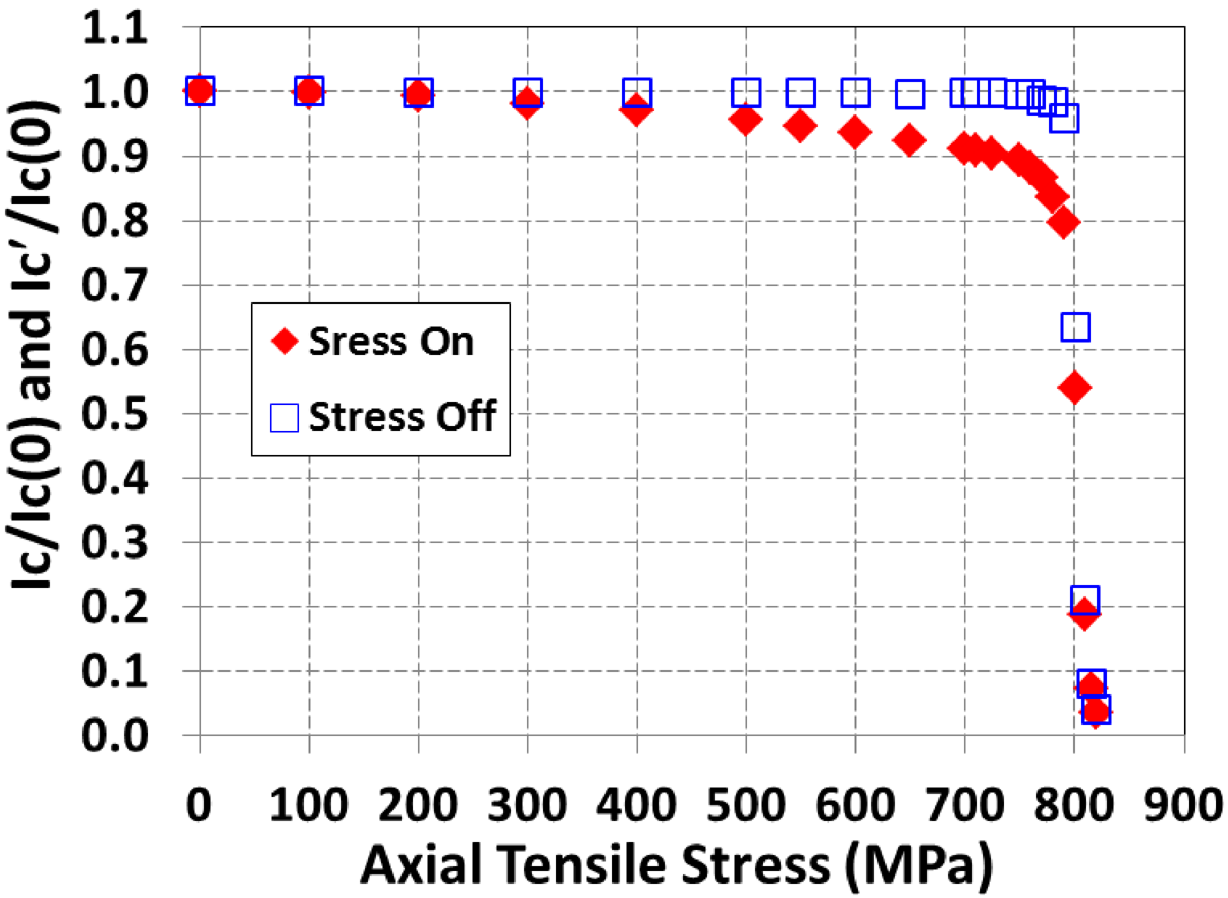
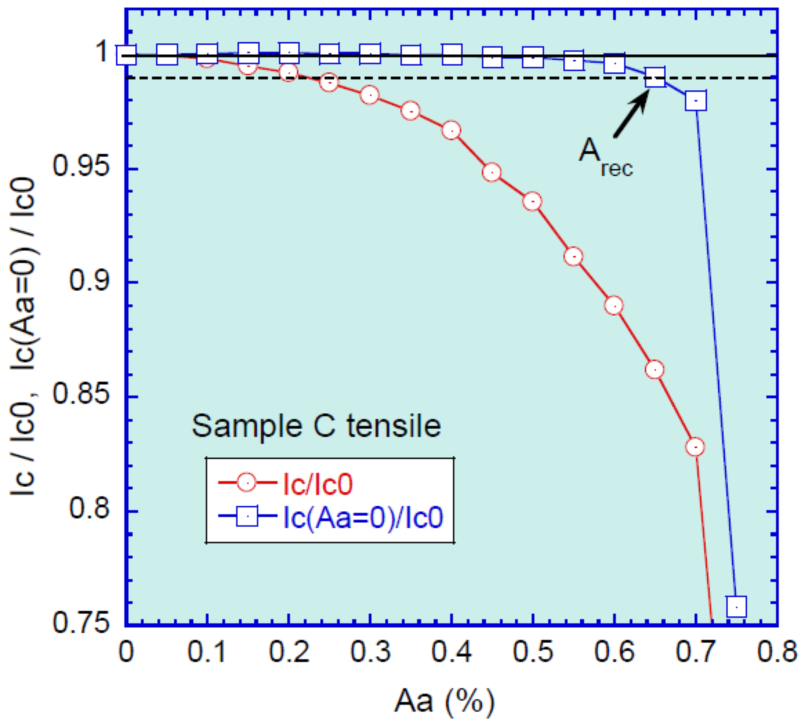
Measuring effects of tensile stress (strain) on critical current

- $I_c(0)$ – original critical current of as-received wire
- I_c – critical current measured while a wire is under a stress (strain)
- I_c' – critical current measured after a stress (strain) is completely released

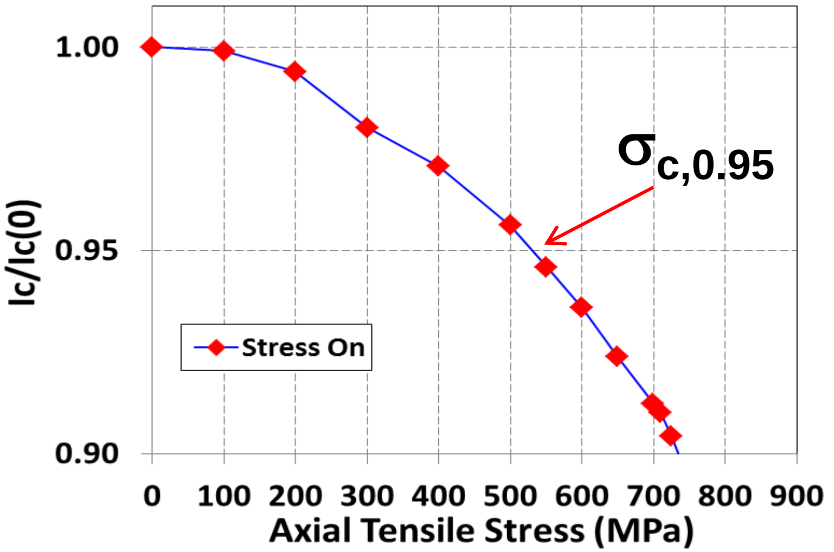


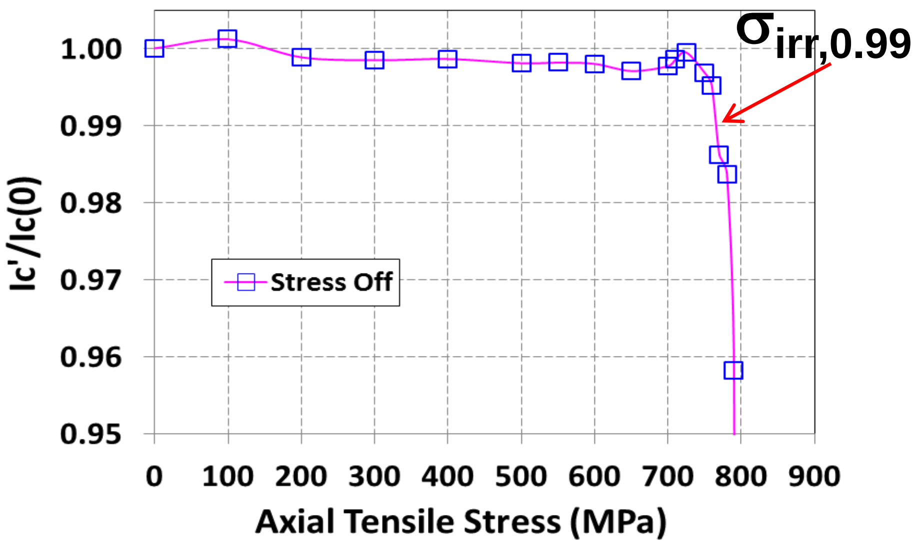
Defining critical stress (strain) and irreversible stress (strain)

- $\sigma_{c,0.95}$ and $\varepsilon_{c,0.95}$ are stress and strain at which $I_c = 0.95 I_c(0)$
- $\sigma_{irr,0.99}$ and $\varepsilon_{irr,0.99}$ are stress and strain after which $I_c' = 0.99 I_c(0)$



K. Osamura, CCA 2014, presentation ST_IS_004





Measurements done in this work

Materials and temperature & field

- 2G HTS wires on 50µm thick Hastelloy substrate and with variation in stabilizer thickness (total Cu thickness = 0, 20, 40, or 100µm)
- At 77K in liquid nitrogen, self-field

Behaviors and properties

- Stress-strain relationship and the mechanical properties
  - Yield stress ($\sigma_{0.2}$, $\sigma_{0.1}$)
  - Elastic modulus ($E_{0.45}$)
- Critical current (77K, self-field) measured under uniaxial stress of different levels and the critical stress (strain)
  - $I_c/I_c(0) \sim \sigma$ and $I_c/I_c(0) \sim \varepsilon$
  - $\sigma_{c,0.95}$ and $\varepsilon_{c,0.95}$
- Critical current (77K, self-field) measured after release of uniaxial stress of different levels and the irreversible stress (strain)
  - $I_c'/Ic(0) \sim \sigma$ and $I_c'/I_c(0) \sim \varepsilon$
  - $\sigma_{irr,0.99}$ and $\varepsilon_{irr,0.99}$

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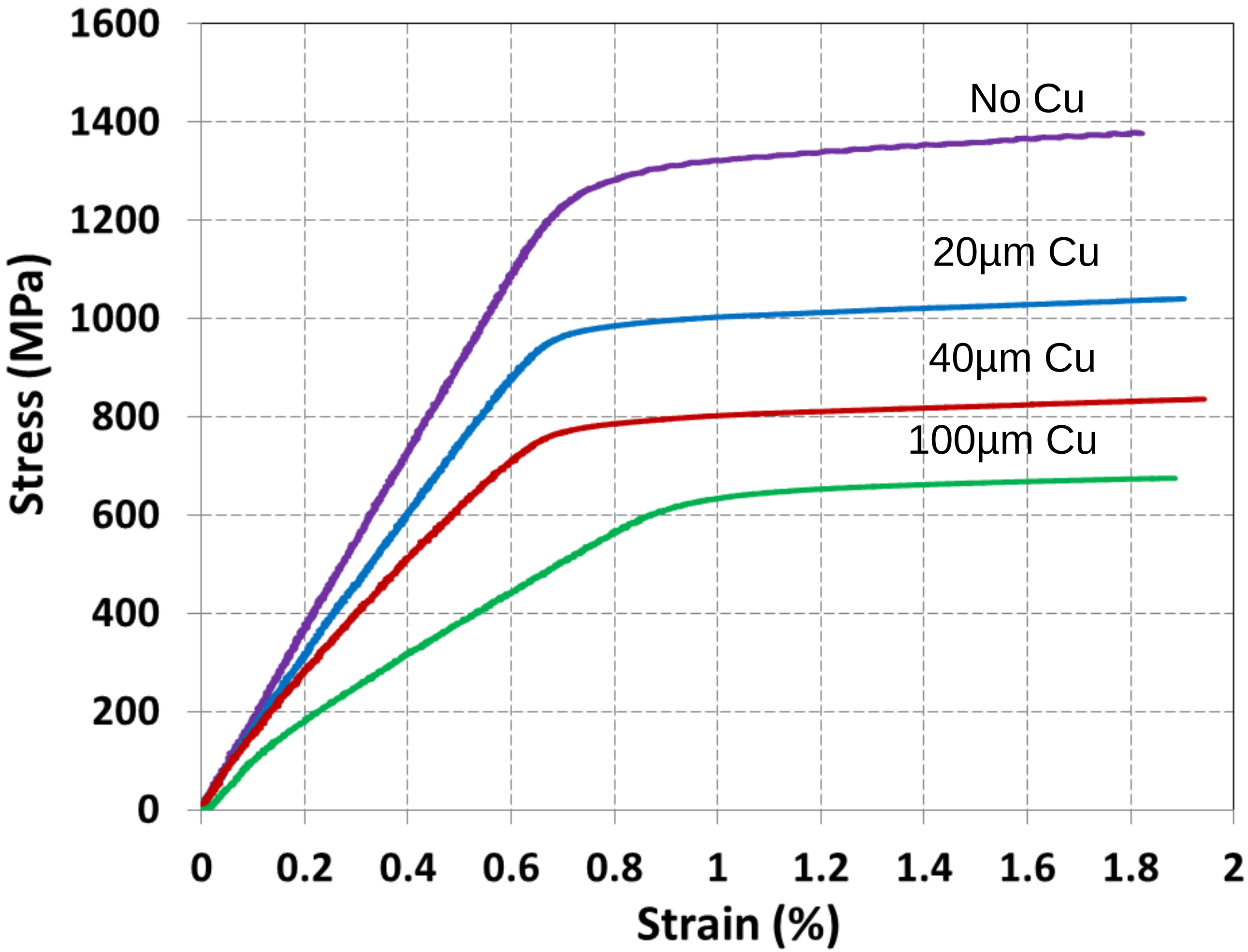
Stress-strain relationship at 77K in LN2

Under static monotonic uniaxial loading



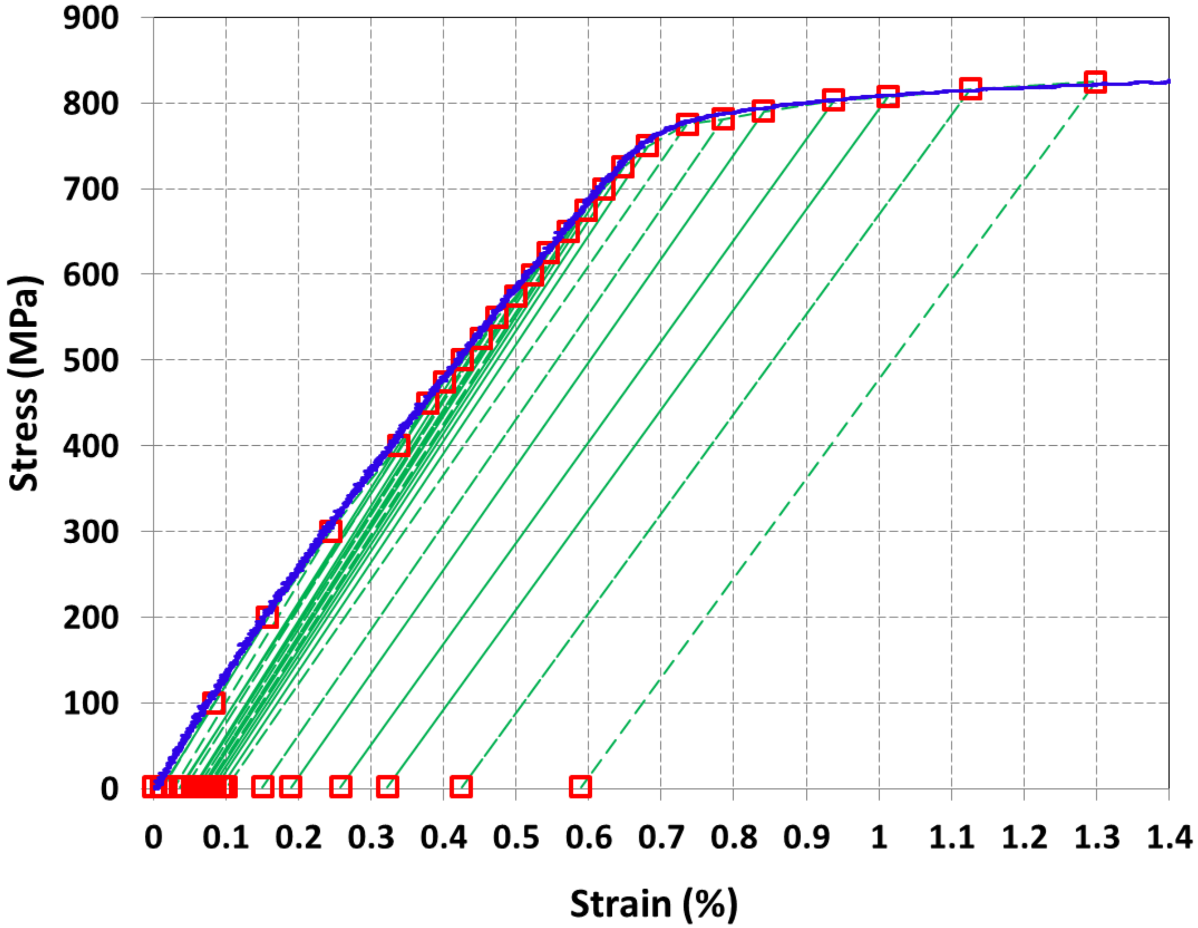
Mechanical Properties

- Yield stress
  - $\sigma_{0.1}$
  - $\sigma_{0.2}$
- Elastic Modulus
  - Chord modulus, e.g., $E_{0.45}$ (ASTM E111-04)

All on 50µm thick Hastelloy substrate with variation in total Cu stabilizer thickness

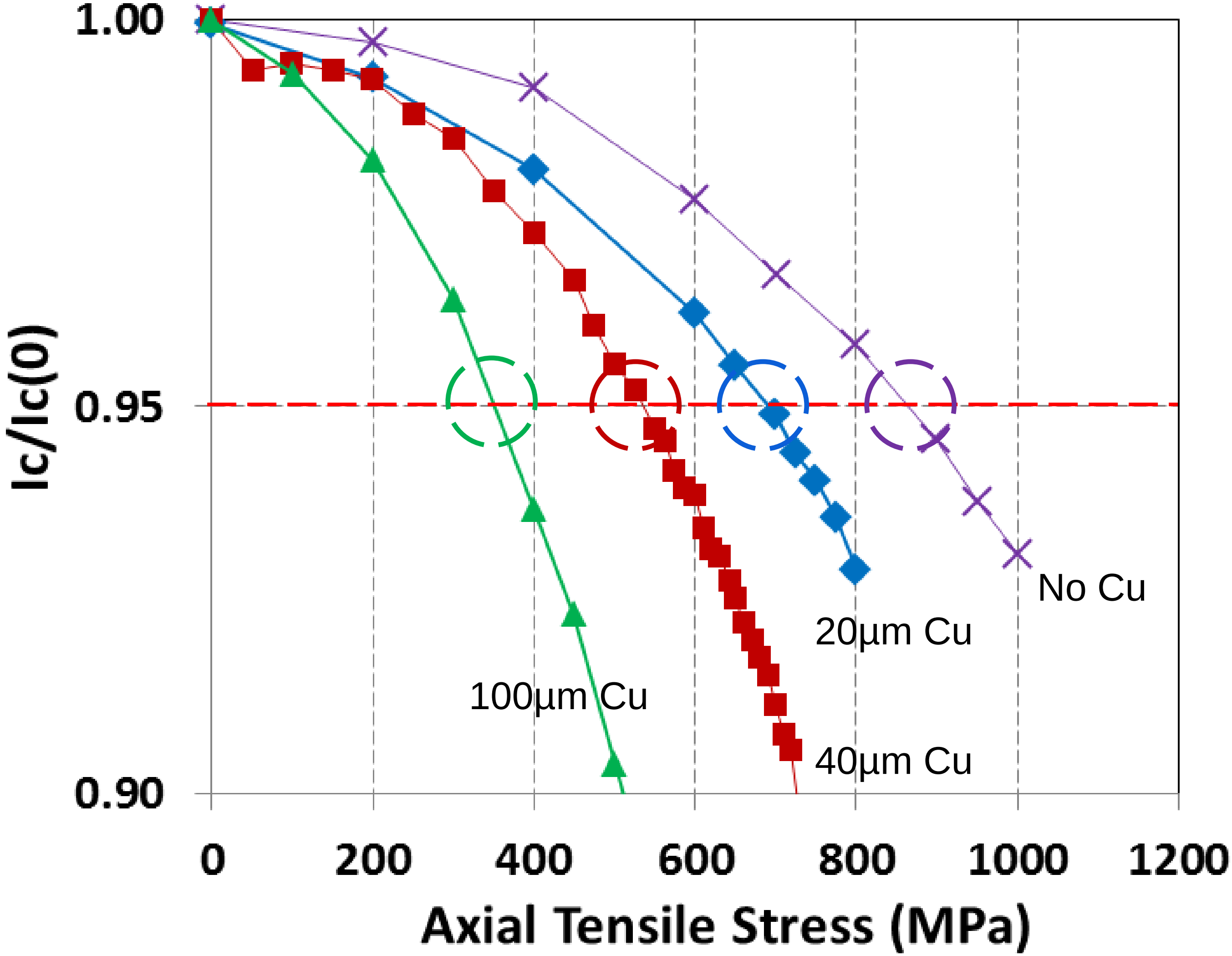
Stress-strain relationship at 77K in LN2

Through loading-unloading with progressively higher load level



SCS12050 wire with total 40µm thick Cu stabilizer

$I_c/I_c(0)$ vs. stress, and $\sigma_{c,0.95}$ (critical stress)



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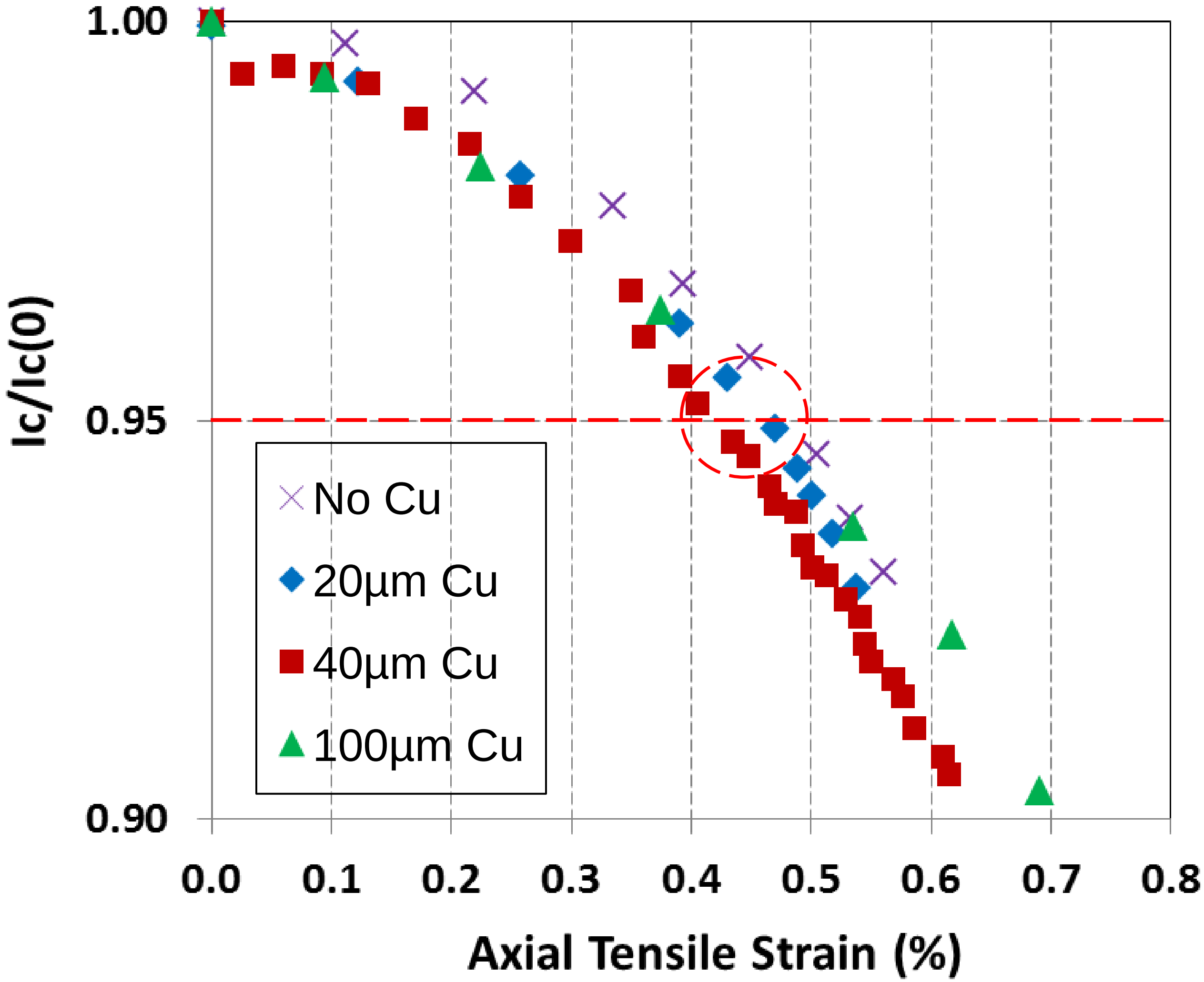
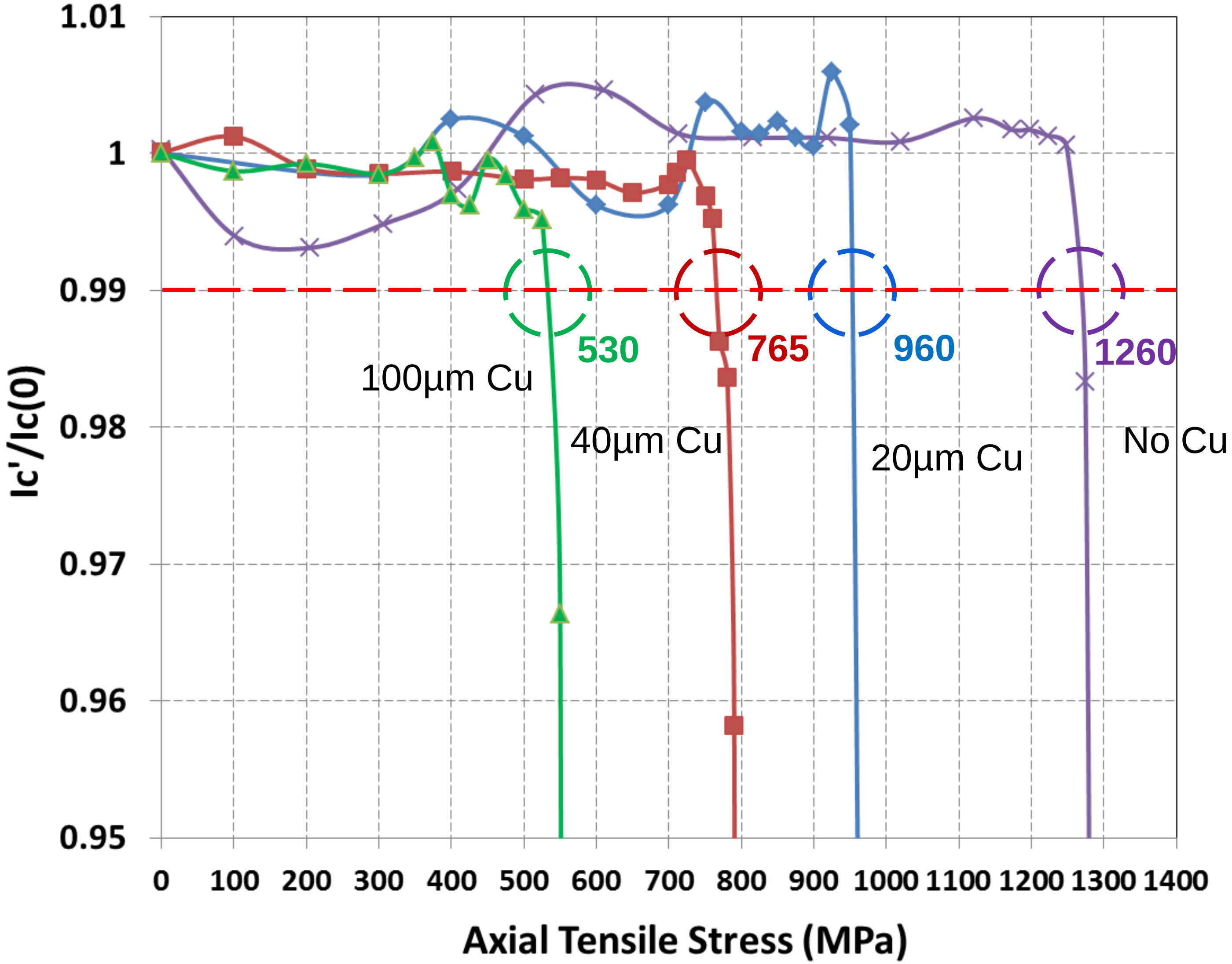
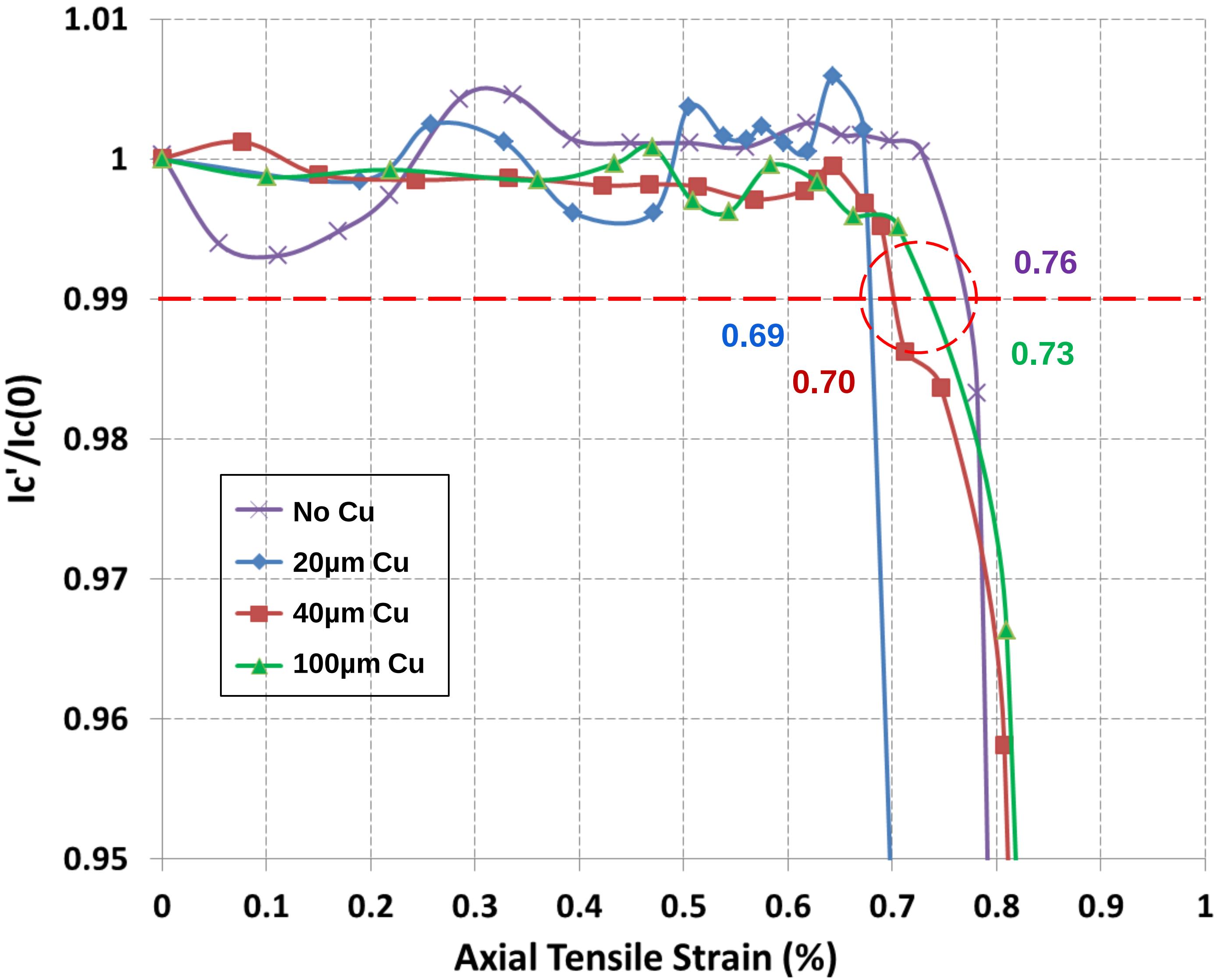
$I_c/I_c(0)$ vs. strain, and $\varepsilon_{c,0.95}$ (critical strain)



$I_c'/I_c(0)$ vs. stress, and $\sigma_{irr,0.99}$ (irreversible stress)



$I_c'/I_c(0)$ vs. strain, and $\varepsilon_{irr,0.99}$ (irreversible strain)



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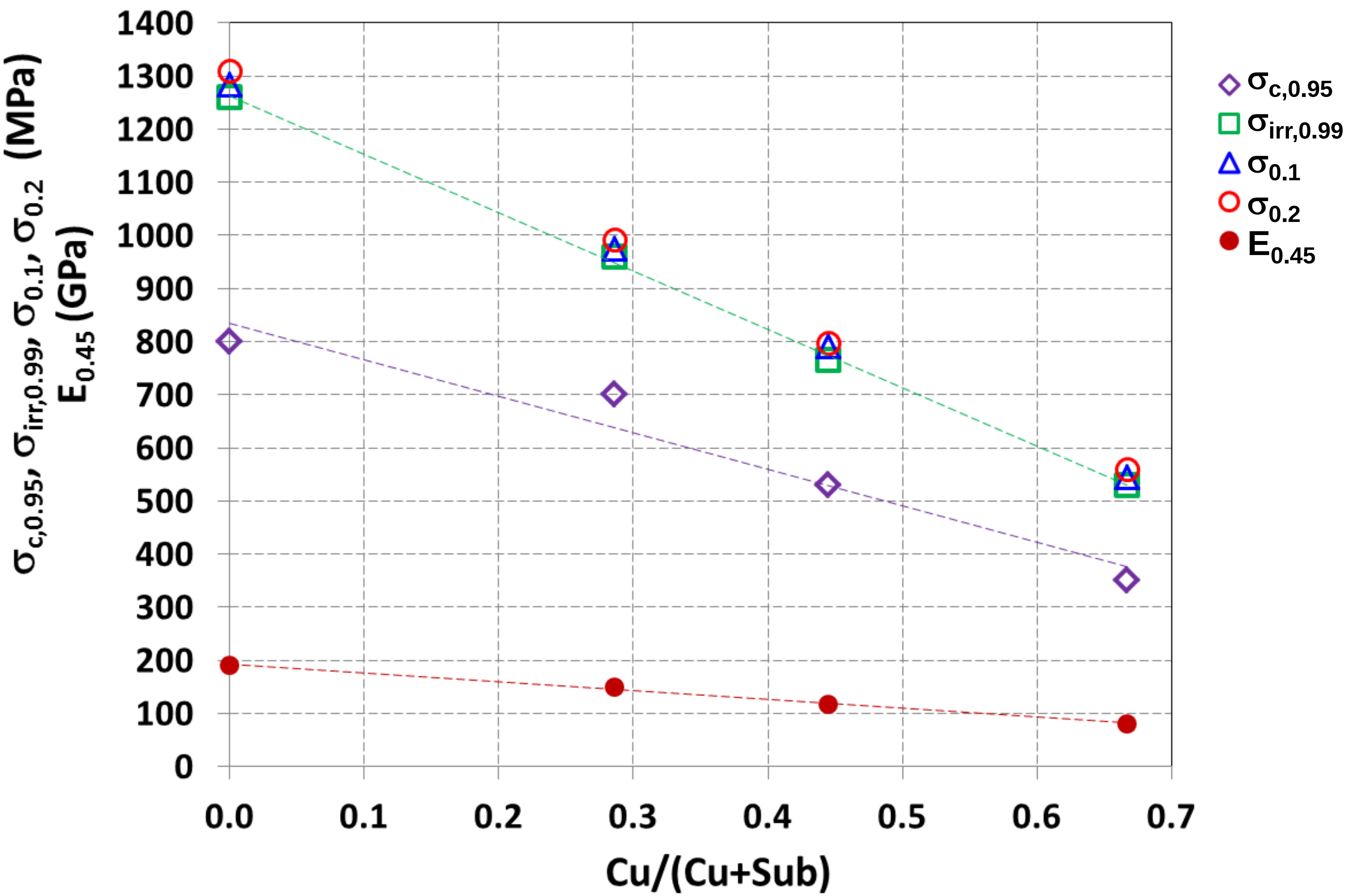
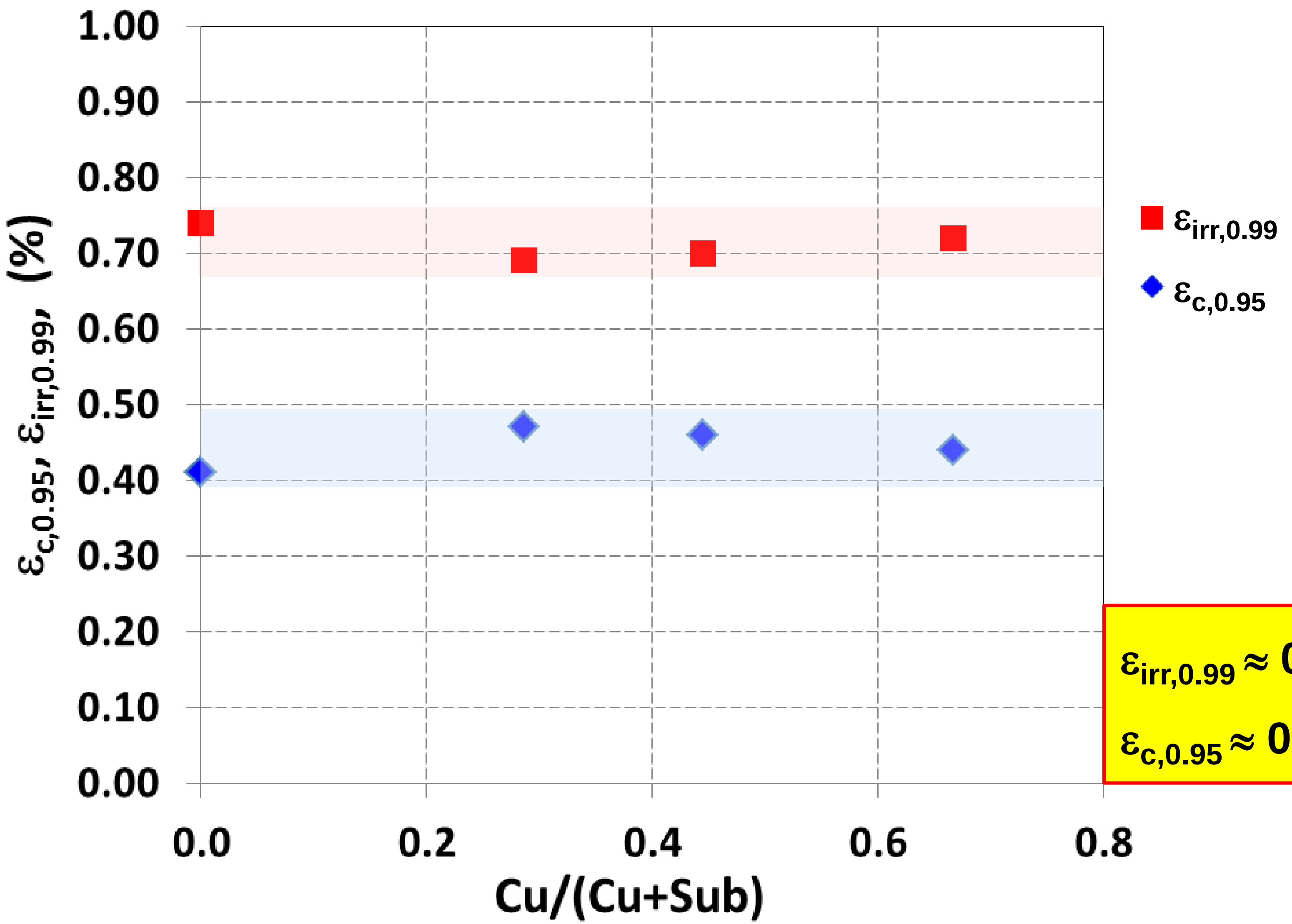
Effect of Cu stabilizer thickness on MEM properties



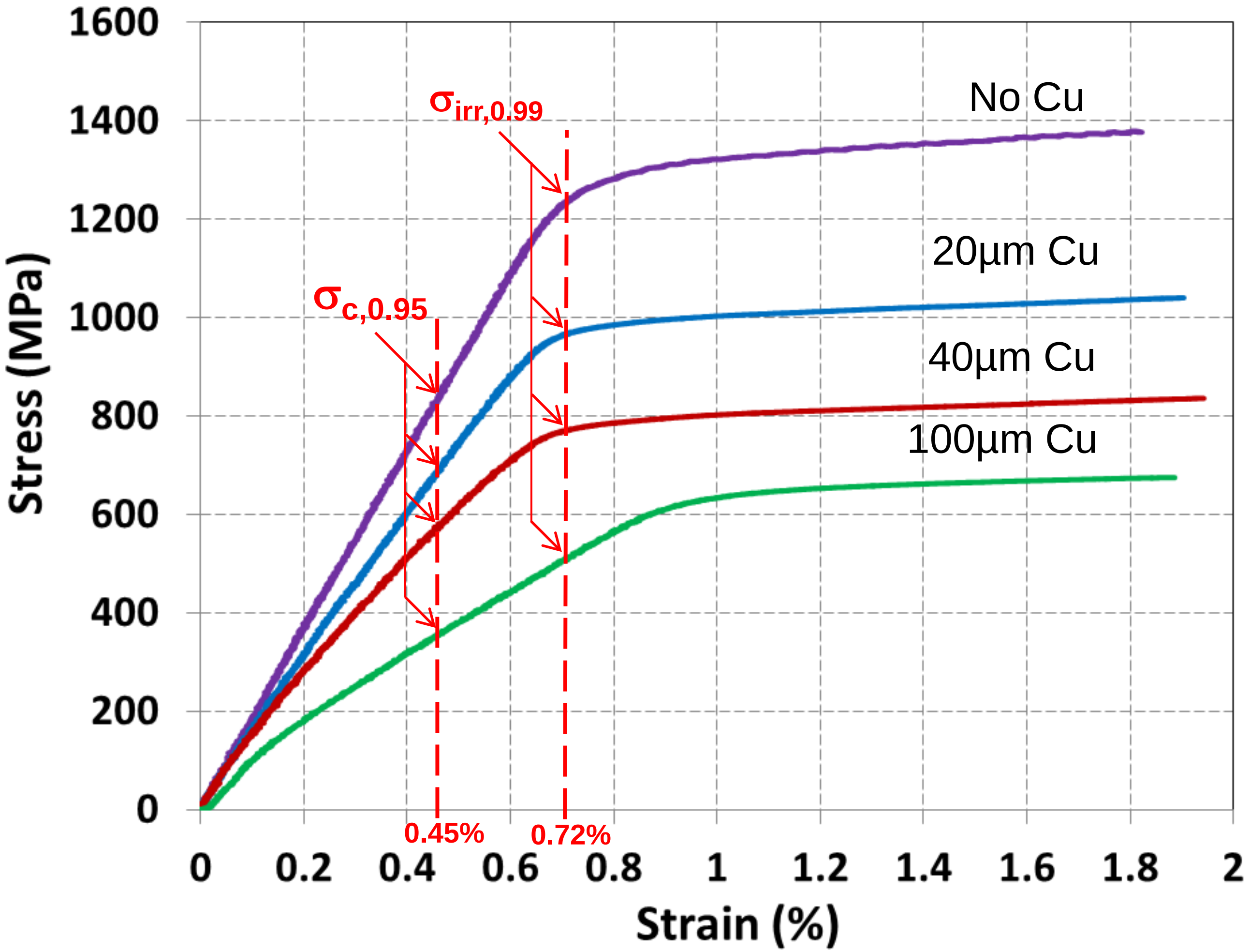
Constant $\varepsilon_{irr,0.99}$ and $\varepsilon_{c,0.95}$, independent of Cu thickness



$\varepsilon_{irr,0.99} \approx$ **0.72%**

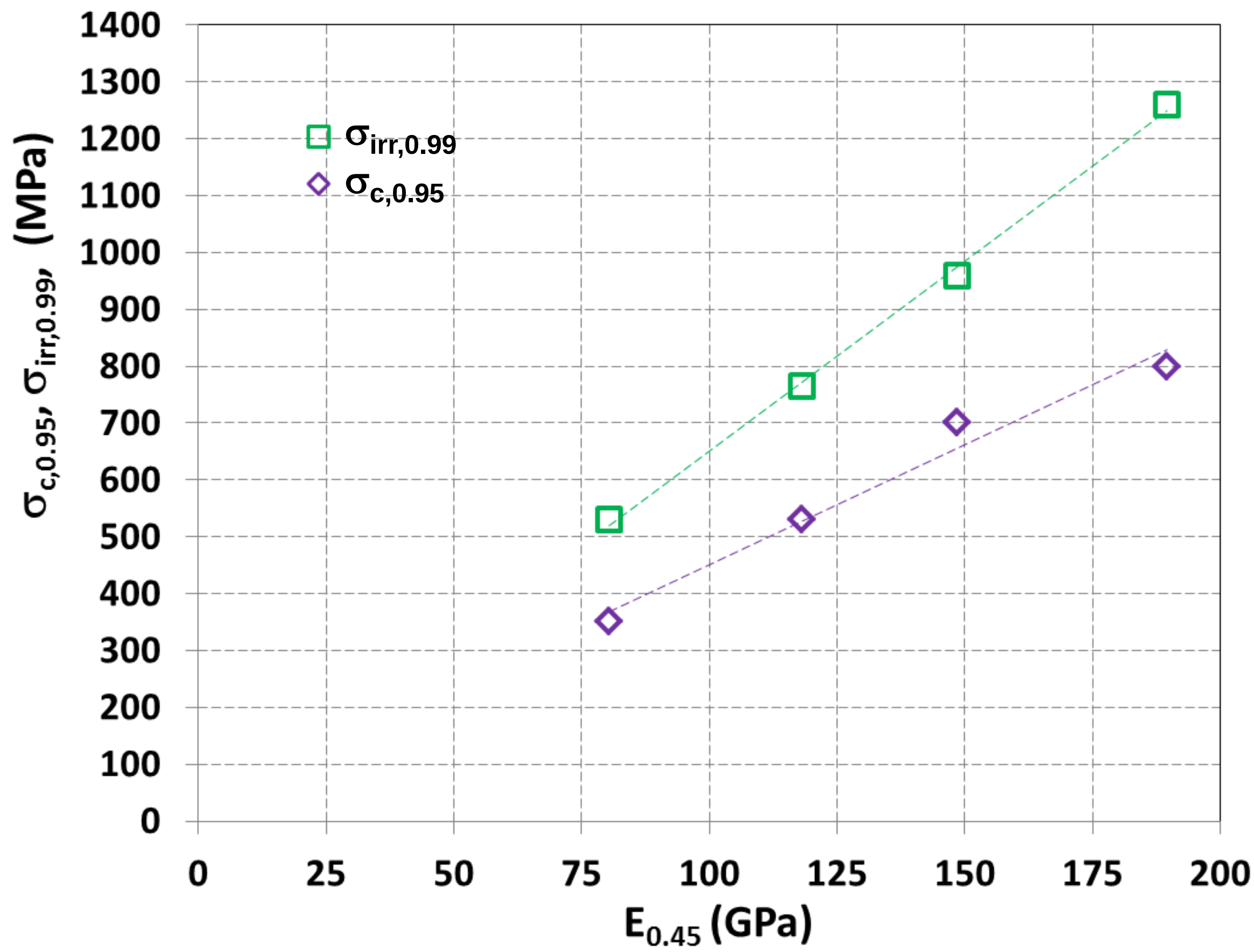
$\varepsilon_{c,0.95} \approx$ **0.45%**

$\sigma_{c,0.95}$ and $\sigma_{irr,0.99}$ on stress-strain curves



All on 50µm thick Hastelloy substrate with variation in total Cu thickness

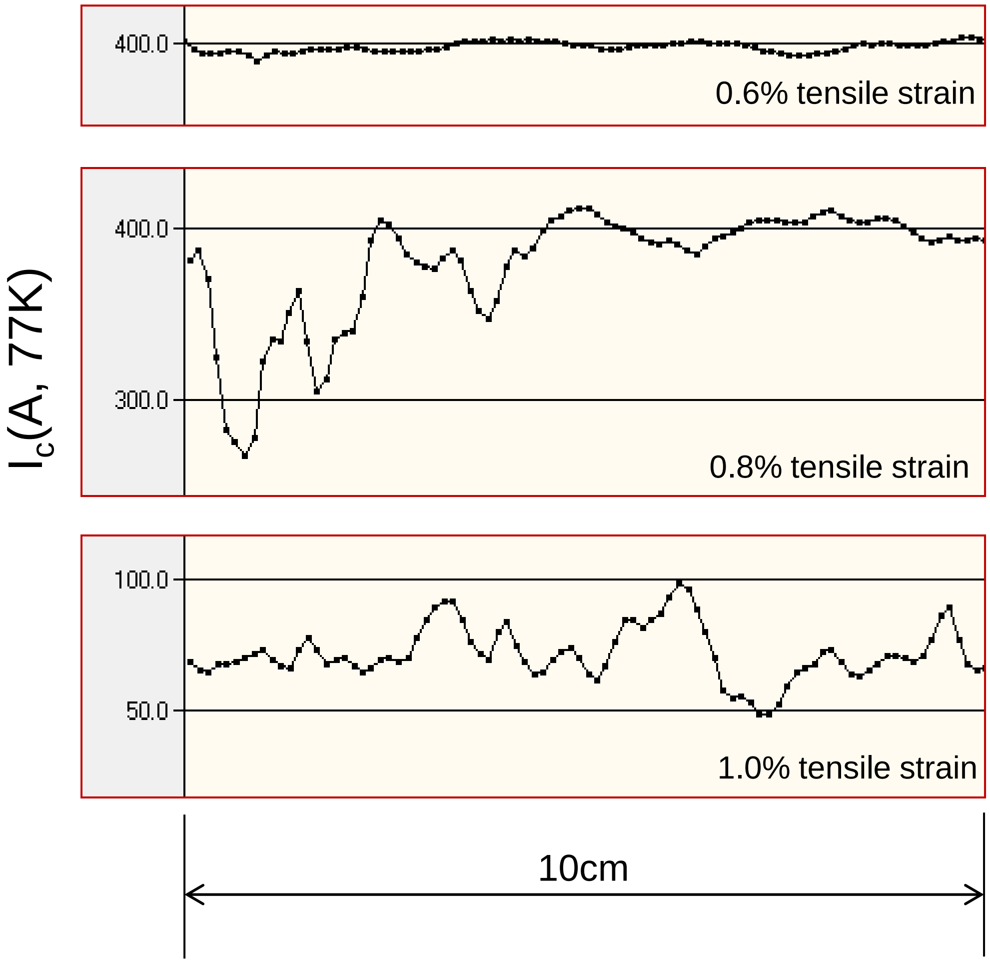
Relationship between $\sigma_{c,0.95}$, $\sigma_{irr,0.99}$ and $E_{0.45}$

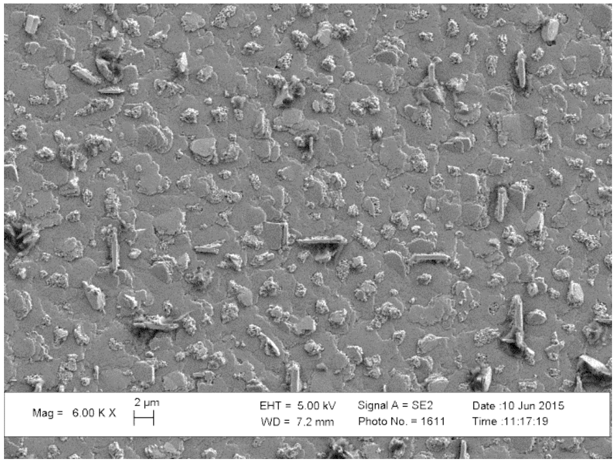


All on 50µm thick Hastelloy substrate with variation in total Cu thickness

$I_c(x)$ on tensile tested samples

- I_c along length measured for tensile tested samples using TapeStar
- REBCO surfaces of tested samples inspected by SEM





SEM image of REBCO surface 0.75% strain

No micro cracks were found on REBCO surface for samples been up to around $\varepsilon_{irr,0.99}$

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Summary

- Testing capabilities have been established at SuperPower to measure and study the mechanical and electromechanical (MEM) properties of 2G HTS wires under various types of loads
  - Uniaxial tension
  - Torsion + axial tension
  - Transverse tension
  - Transverse compression
- The effects of Cu stabilizer thickness, or the Cu/(Cu+Sub) ratio on the MEM properties of 2G HTS wires under uniaxial tension were studied at 77K
  - Elastic modulus and yield stress decrease with increasing Cu thickness
  - Critical stress ($\sigma_{c,0.95}$) and irreversible stress ($\sigma_{irr,0.99}$) decrease with increasing Cu thickness, depend linearly on elastic modulus $E_{0.45}$
  - Critical strain ($\varepsilon_{c,0.95}$) and irreversible strain ($\varepsilon_{irr,0.99}$) are independent of Cu thickness, showing intrinsic values at 0.45% and 0.72%, respectively