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Development of Testing Method for Adhesion Strength Characterization of 2G HTS Wires

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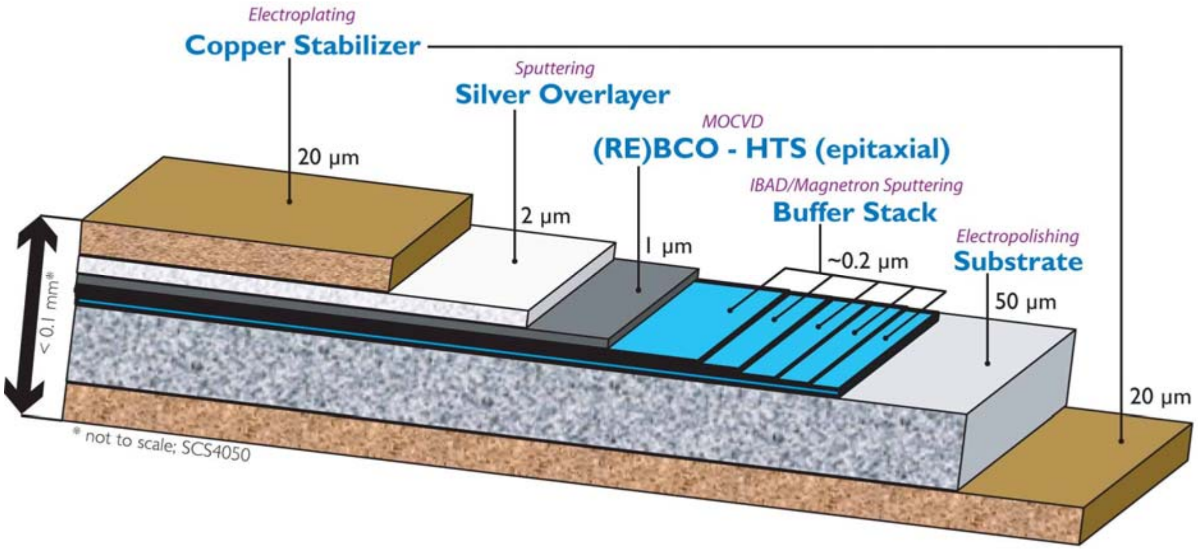
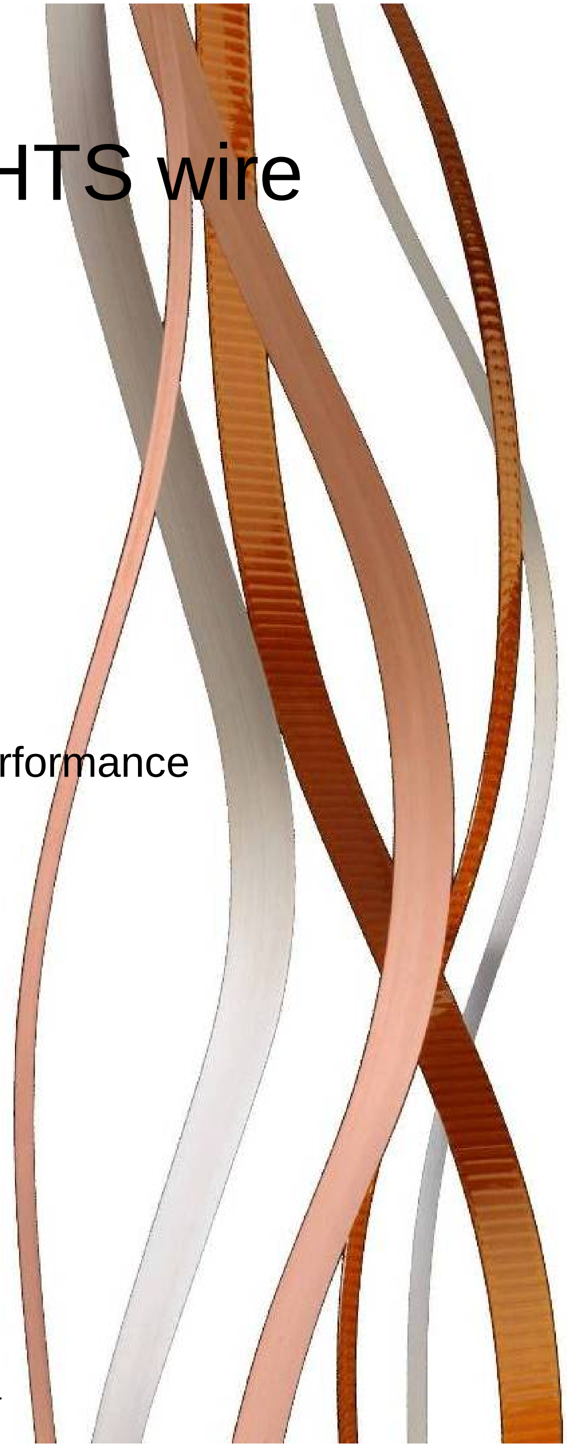
Outline

- Introduction
- Mechanical properties of 2G HTS wire
- Coil degradation and wire delamination
- Transverse tensile strength testing
- Peel test – method & evaluation
- Peeling angle and weakest interface
- Improvement of adhesion strength (peel strength)
- Summary

SuperPower's technologies for 2G HTS wire manufacturing

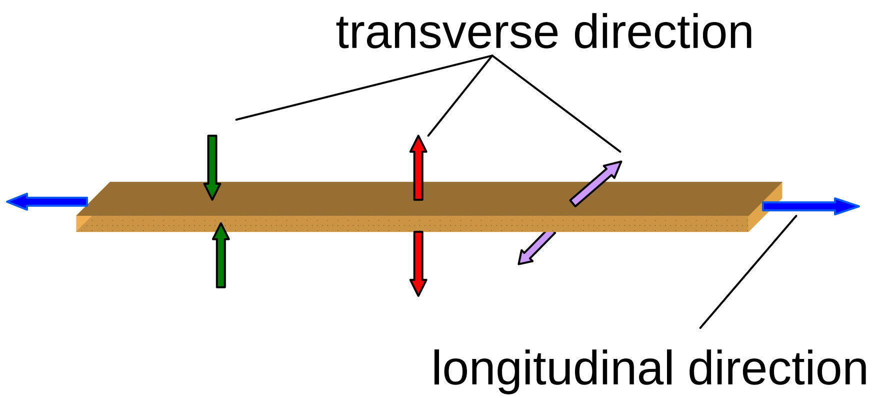
- Hastelloy substrate prepared with electropolishing
- Epitaxial template achieved by IBAD-MgO
- REBCO film deposited by MOCVD
- Sputtered Ag and electroplated surround Cu stabilizer
- Automated reel-to-reel long-length wire mass production
- Real time & integrated quality control and monitoring
- Wire testing & characterization
- High engineering current density & superior in-magnetic-field performance

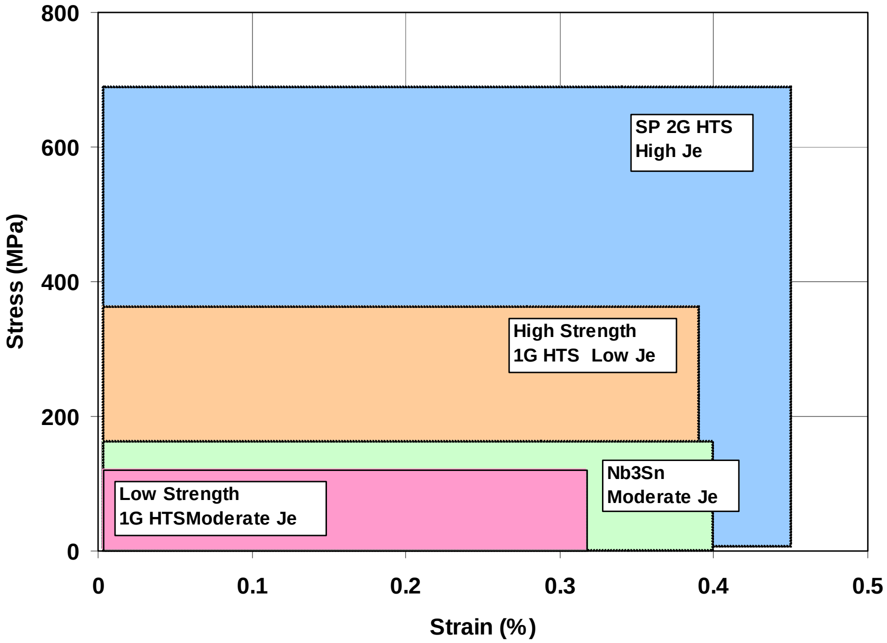




Mechanical property requirements for applications

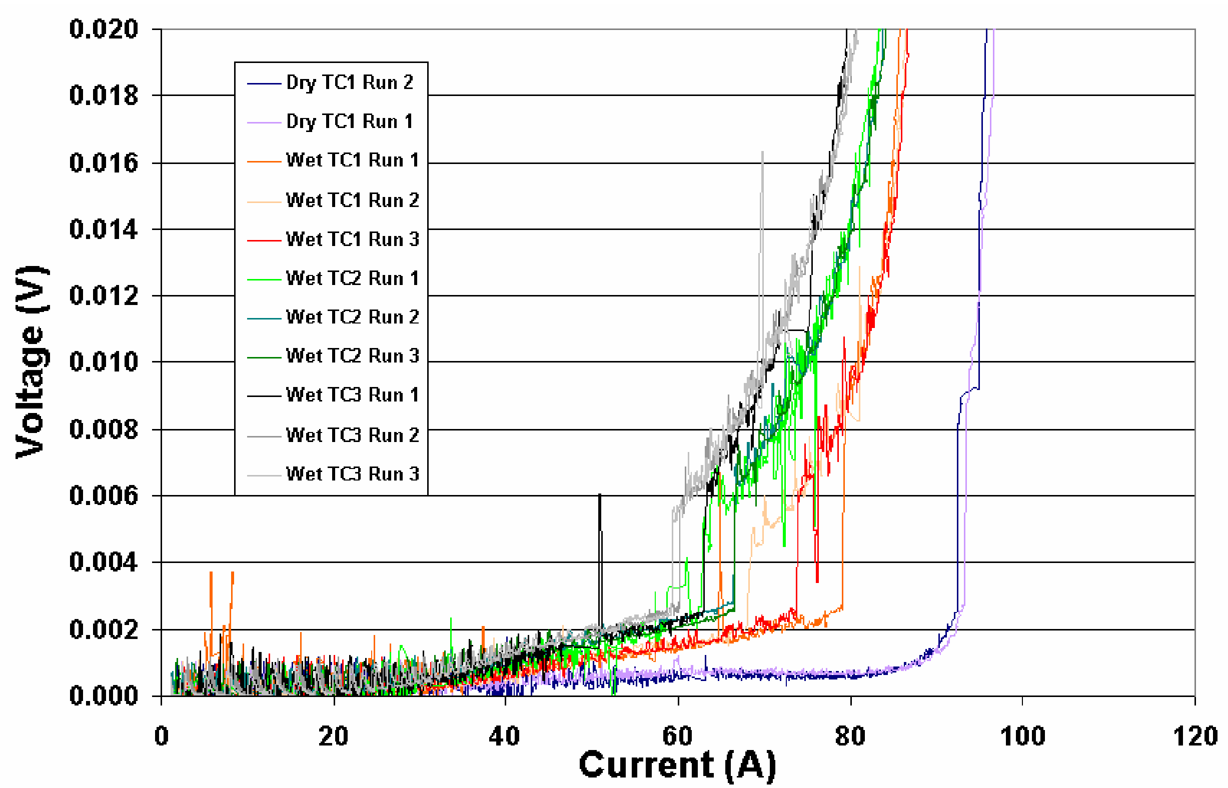
- Longitudinal direction - static tensile stress, cyclic tensile stress
- Transverse direction (perpendicular to the surfaces) - static tensile stress, static compressive stress, cyclic tensile stress, shear stress
- Transverse direction (parallel to the surfaces) - shear stress
- Bending - tensile & compressive bending stresses





Coil performance, wire delamination and adhesion strength

- Coil I_c drops through thermal cycling between RT and 77K;
- Degradation occurs only to epoxy wound or impregnated coils;
- Believed to be due to transverse tensile stress originated from difference in coefficients of thermal expansion.



I-V curves of dry- & wet-wound coils

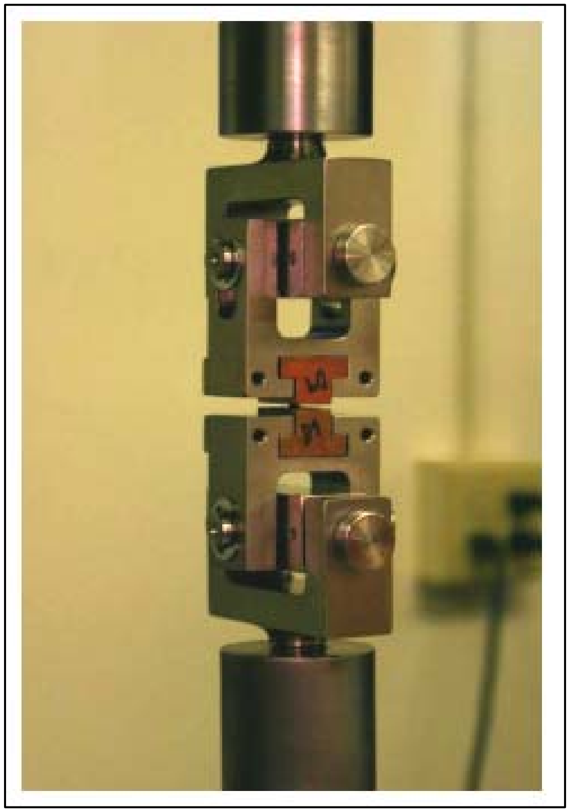
Measurement of adhesion strength – testing method overview

- Mechanical strength against delamination: Terminologies
  - Adhesion strength
  - Delamination strength
  - Transverse tensile strength
  - *C*-axis tensile strength
  - Peel strength
  - Cleavage strength

- Mechanical strength against delamination: Testing methods
  - Anvil Test (NIST, UC, SRL-ISTEC, NHMFL w/Ic)
  - Pin-Pull Test (SP)
  - Stud-Pull Test (Fujikura)
  - Cleavage Test (RIKEN w/Ic)
  - Peel Test (SP)
  - Four Points Bending Test (SRL-ISTEC)
  - Double Cantilever Beam (DCB) Test (Kyoto University)

Measurement of adhesion strength
– limitation of anvil test & pin-pull test

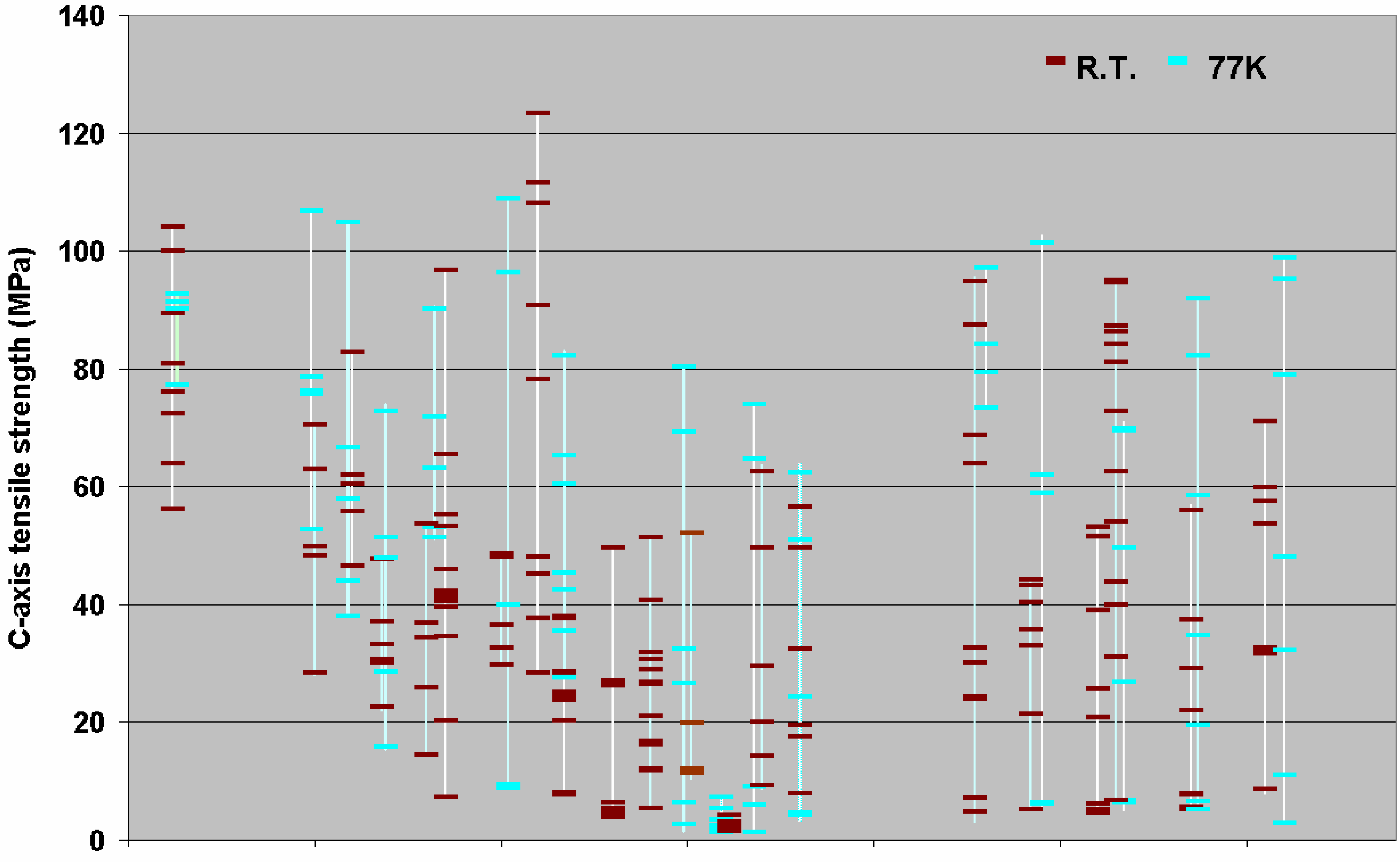
- Reliability – data spreads in a large range (RSD=25~50%), results depends on sample preparation, mounting and stress concentration & distribution;
- Correlation – lack of correlation with coil performance and lack of sensitivity to differentiate between wires.



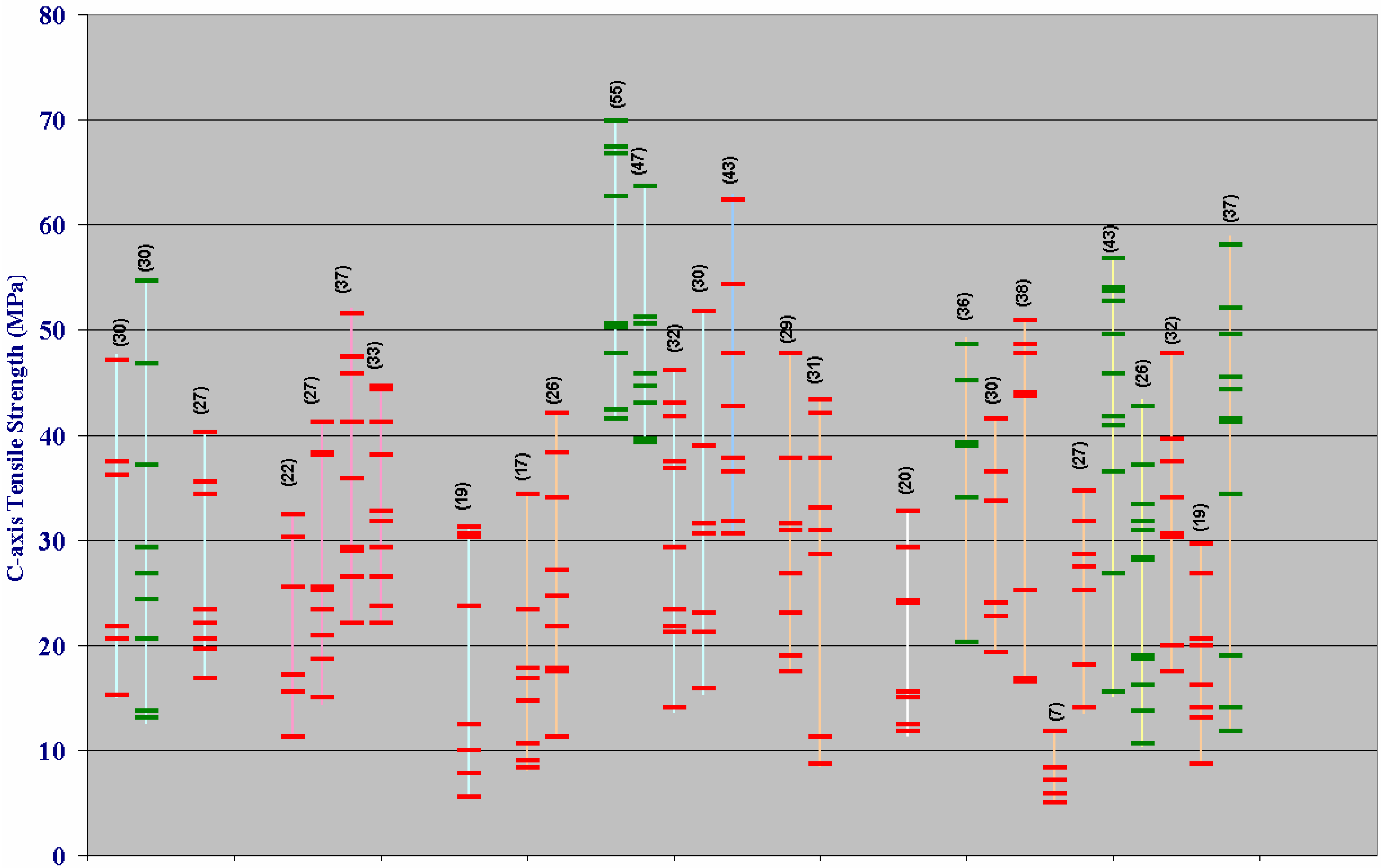
Anvil Test

Pin-Pull Test

Results from anvil test



Results from pin-pull test



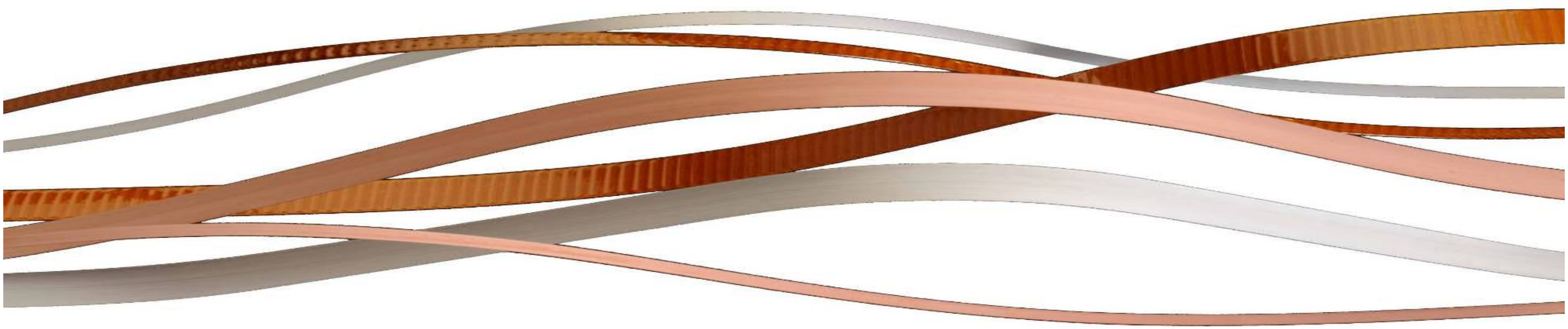
Sources of uncertainty for pin-pull test

- C-axis Tensile Strength* Data** Uncertainty
  - Wire
    - Tape Uniformity (along length)
    - Tape Uniformity (across width)
    - Edge Effect
  - Fabrication
    - Effective Solder Joint Area
    - Stress concentration & distribution
    - Tape/Pin Alignment
    - Tape/G10-Plate Alignment
  - Testing
    - Load/Pin Alignment
    - Loading Speed

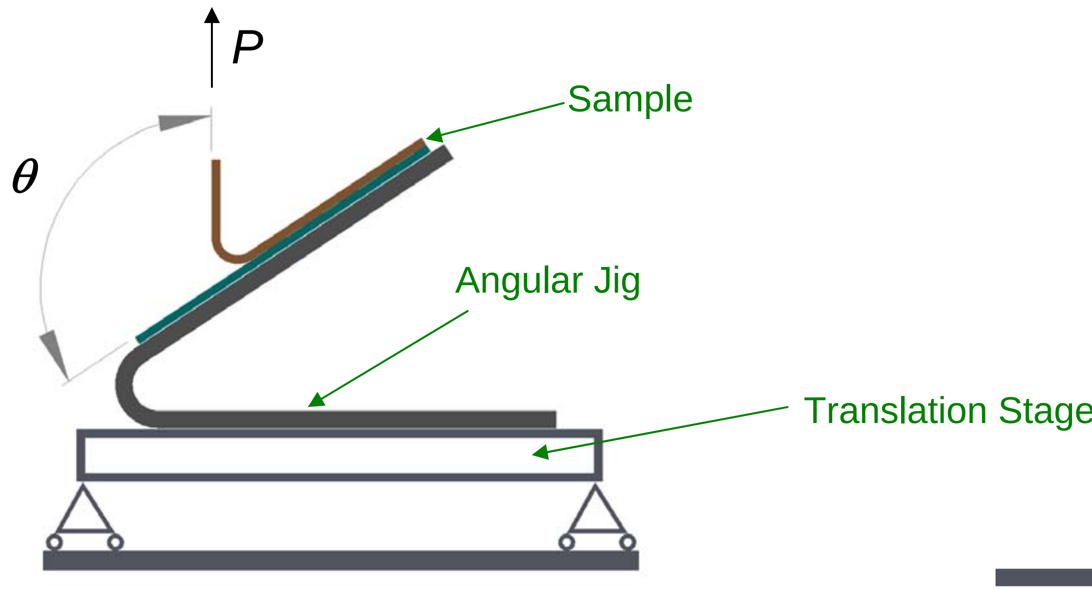
*** Strength defined as (peak load)/(nominal solder joint area) based on the solder-pin pull test**
**** Data obtained from a group of around 10 samples fabricated with a same wire**

Measurement of adhesion strength – requirements on testing method

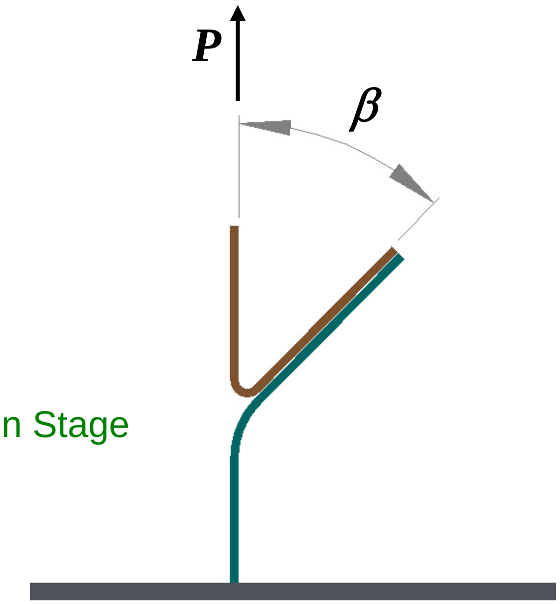
- Quantification – well defined quantitative values for evaluation and comparison;
- Reliability – reproducible data with minimized effects from sample preparation, fixture alignment, mounting and handling (operator);
- Sensitivity – accurate enough to differentiate between wires with small difference in the strength;
- Relevance – results closely correlate with coil performance (wire under a stress state similar to that in a coil, at least in the transverse direction).



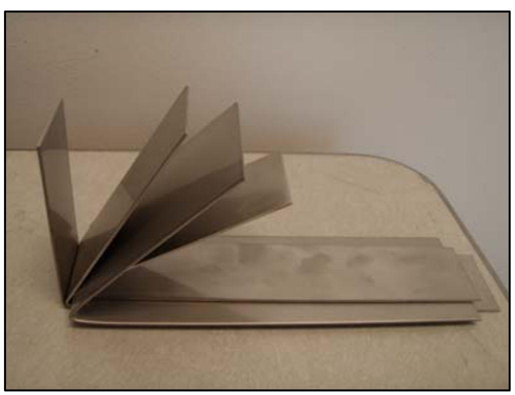
Peel test – method and evaluation



Fixed peeling angle peel test



T-peel test



Angular Jigs

- Tape with ~1mm sheared off at both edges
- Sample total length: 80 ~ 120 mm
- Start initial peeling manually
- Machine-peeled length: 30 ~ 40 mm
- Peeling rate: 0.3175 mm/sec
- Load-Displacement curve automatically recorded
- Load resolution: 0.01N
- Displacement data step size: 0.3175 mm
- Peel strength defined as average load at plateau

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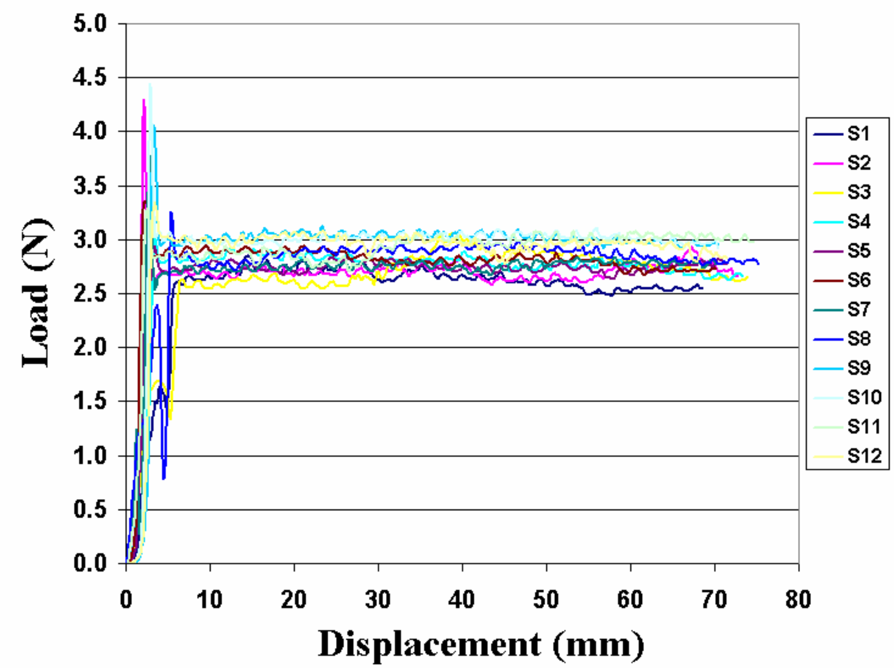
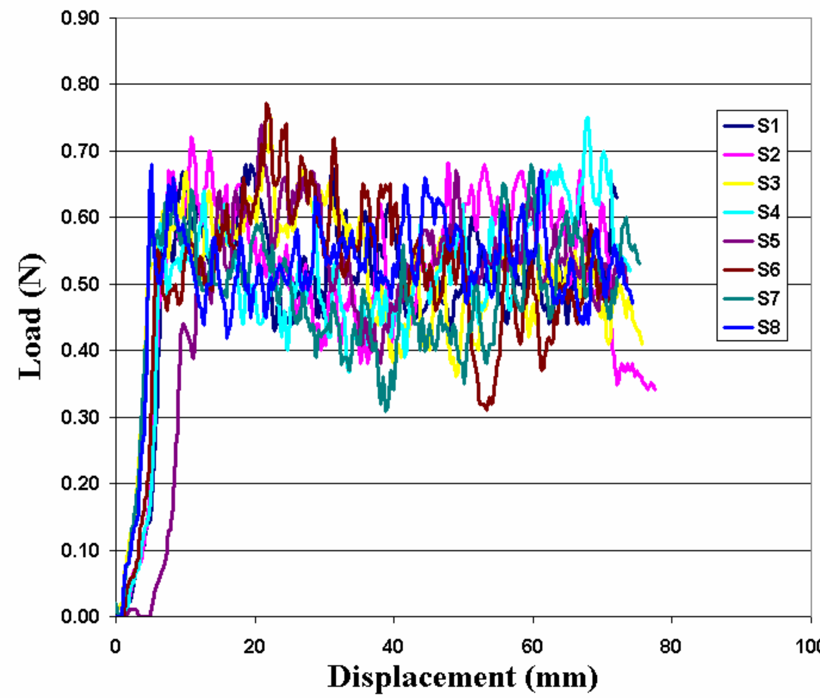
Peel test – method and evaluation (cont'd.)



T-peel test on reference samples fabricated using Kapton adhesive tape/Hastelloy substrate

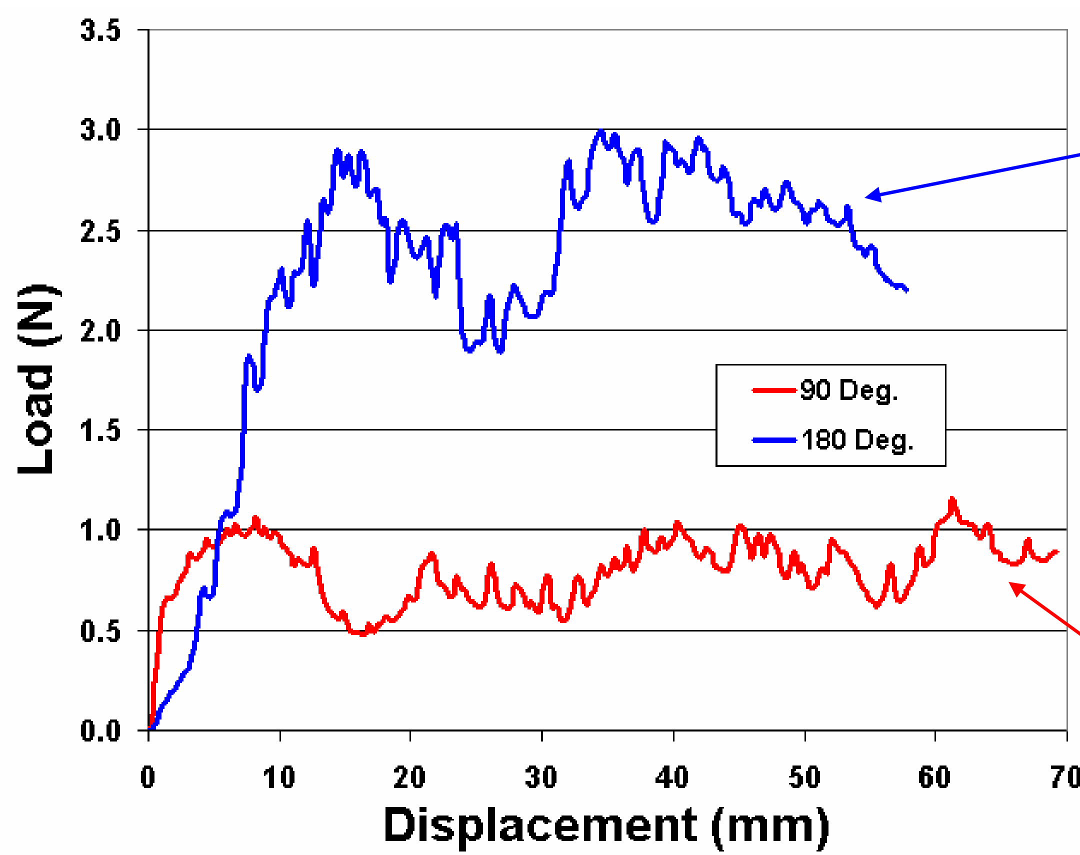


T-peel test on 2G HTS wire

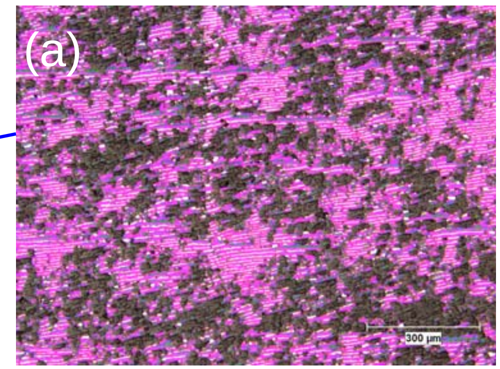
Peel Strength	Mean (N)	STDV (N)	RSD
Ref. Samples	2.84	0.12	4.2%
2G HTS Wire	0.52	0.02	3.8%

Peel test is a reliable and sensitive testing method

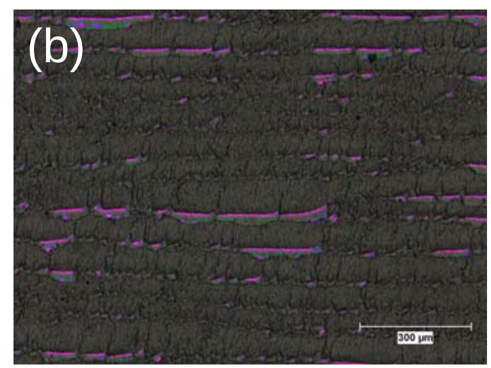
Peel test - effects of peeling angles



Load versus displacement curves for 2G HTS wire



180° peel test



90° peel test

Optical microscopic images of bottom peeled surfaces.

Stress state at peeling front depends on peeling angle

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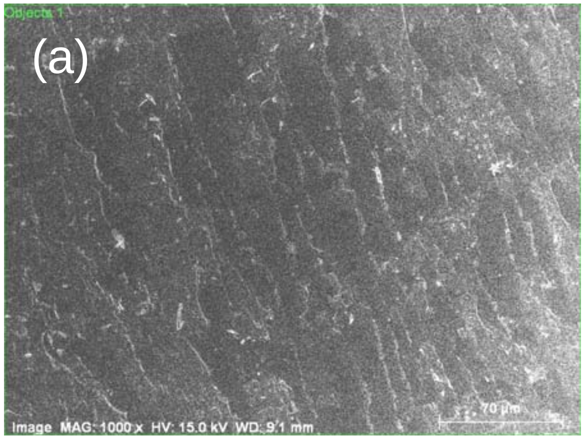
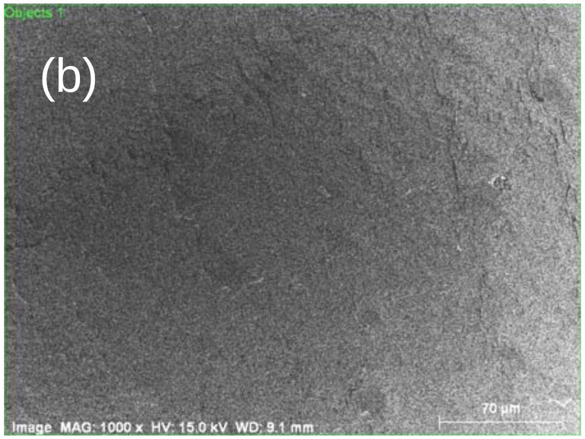
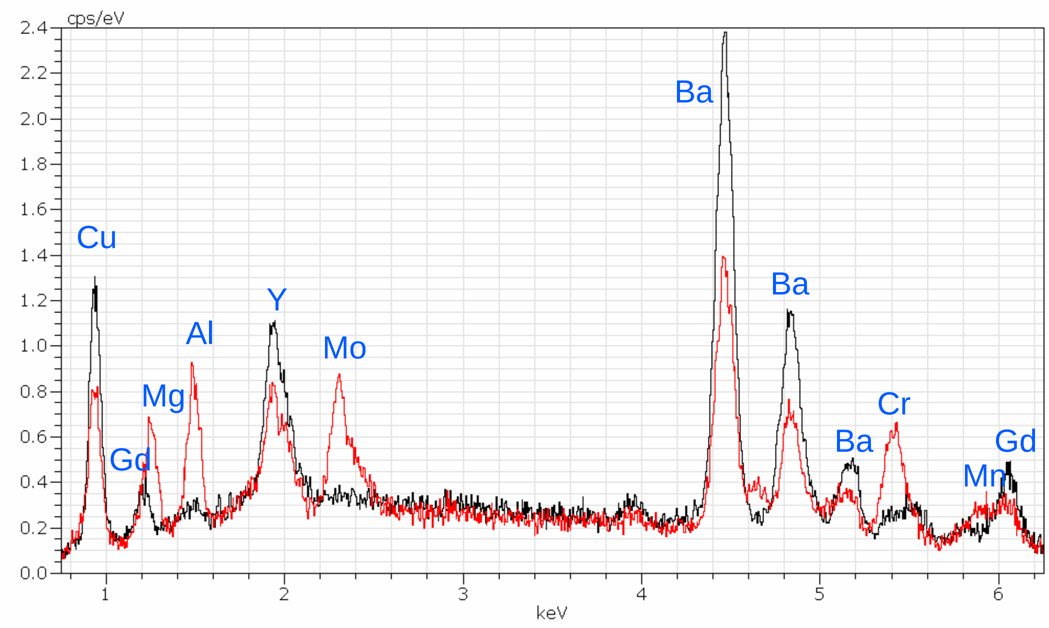
Peel test - identification of weakest interface





SEM images of bottom peeled surfaces from (a) 180°; (b) 90° test



EDS spectra on bottom peeled surfaces from **180°** test and **90°** test.

Peel strength & weakest interface dependent on peeling angle (loading scheme or stress state)

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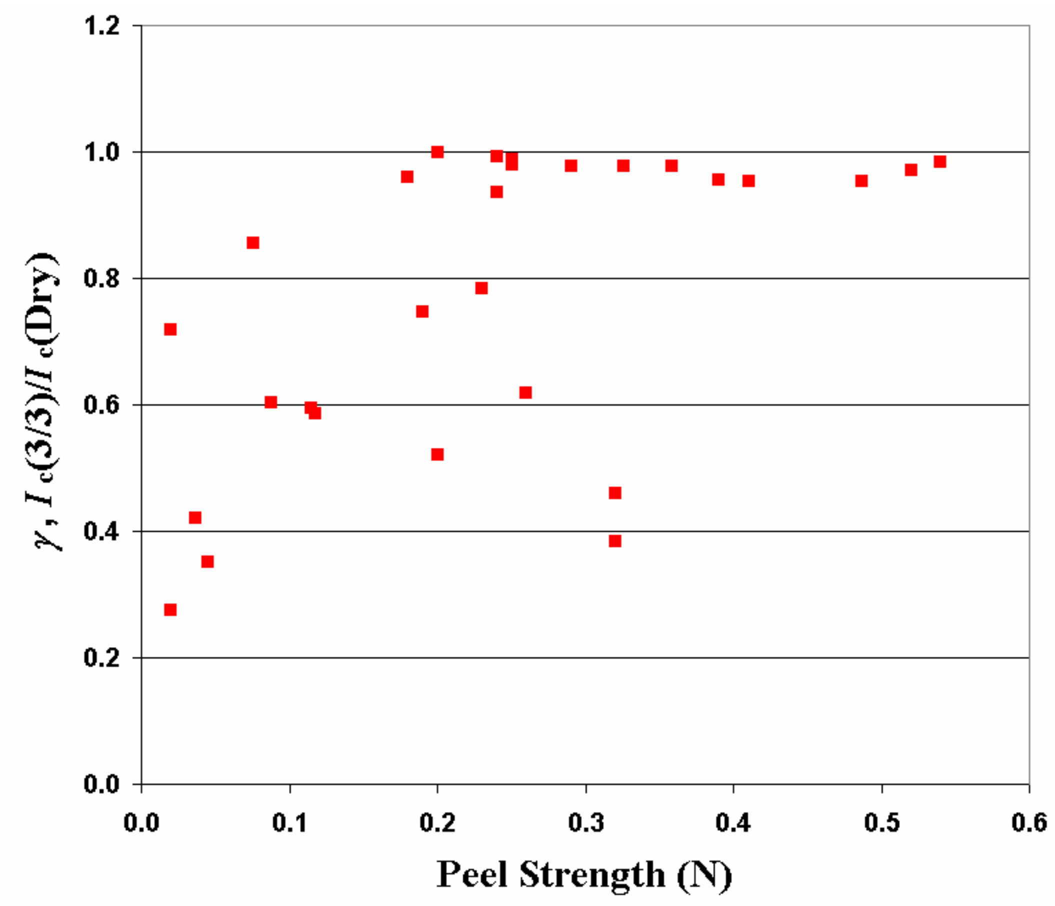
Correlation between coil performance and peel strength



$$\gamma = \frac{I_c(3/3)}{I_c(dry)}$$

$I_c(3/3)$ – critical current from the 3rd measurement at the 3rd thermal cycle from the wet-wound coil

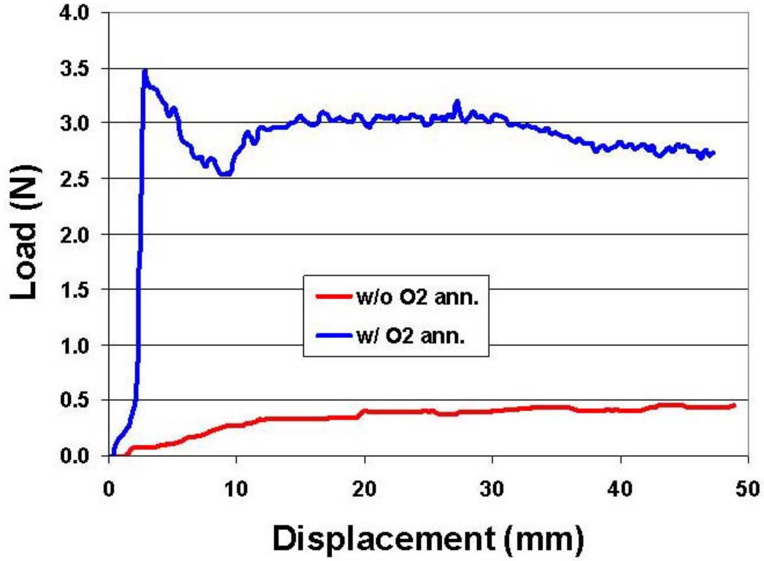
$I_c(dry)$ - critical current from the 1st measurement at the 1st thermal cycle for the dry-wound coil

Relationship between critical current retainability of wet-wound coils through thermal cycling and the peel strength of the corresponding 2G HTS wires

Improvement of adhesion strength (peel strength)

$$P = \eta + \psi$$

P – peel strength;
η – interfacial bonding strength, (interfacial fracture energy);
ψ – mechanical energy dissipated due to material plastic deformation during peeling.



Adhesion strength (peel strength) can be improved by reinforcing the interfacial strength and tuning the mechanical properties of the over layers.

Conclusions

1. Transverse tensile strength (*c*-axis strength, adhesion strength, peel strength) is an important mechanical property, critical to thermal stability of wet-wound and impregnated coils;
2. Peel test is a reliable testing method for studying adhesion strength of 2G HTS wires, with good reproducibility and sensitivity in data;
3. Peel strength and weakest interface (peeling location) are dependent on peeling angle (stress state at peeling front, loading scheme);
4. Correlation was found between wet-wound coil performance and peel strength;
5. Adhesion strength (peel strength) can be improved by reinforcing interfacial bonding strength and tuning the mechanical properties of the over layers.