Materials for Bright Beams Workshop 2025

NATIONAL HIGH MAGNETIC FIELD LABORATORY

High strength/High conductivity copper alloys/composites

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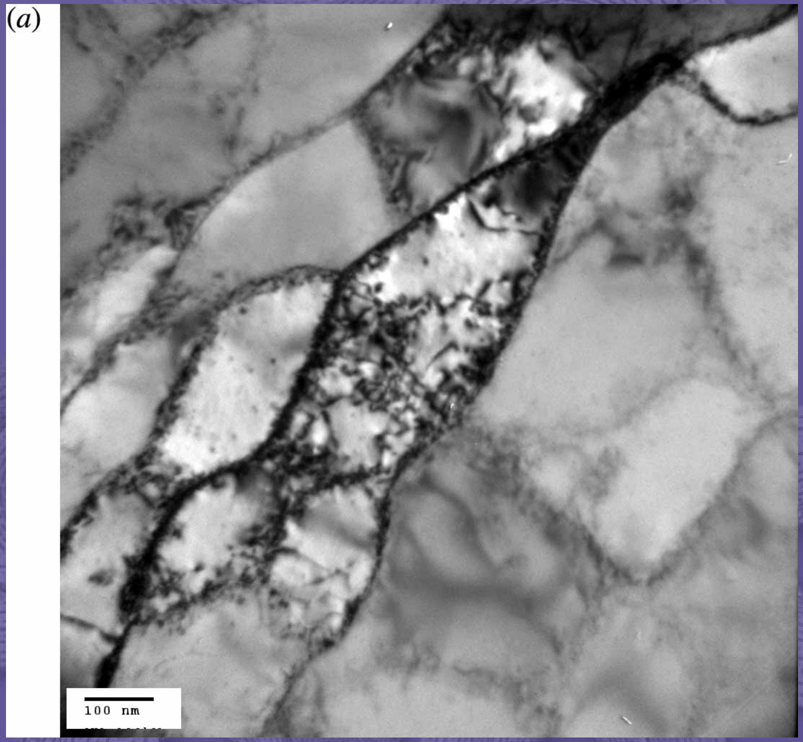
National High Magnetic Field Laboratory is a user facility

- Tallahassee, Florida (FSU)
  - Head quarter, 30000m^2
  - DC and NMR user facility, 20T-41$^+$T
  - 45T, 32mm bore hybrid, 40 MW
- Los Alamos, New Mexico (LANL)
  - Pulsed Field User Facility
  - 40T-75T, ~24-15mm, ~300-30ms
  - 60T, 32mm, ~100ms flat top in rebuilding
  - 85/100T, <20ms
- Gainesvillle, Florida
  - Ultra-low temperature user facility (mK, 500 mK in 16T)

National High Magnetic Field Laboratories in Tallahassee

This presentation focuses on Cu matrix conductors with desirable strength level greater than 400 MPa

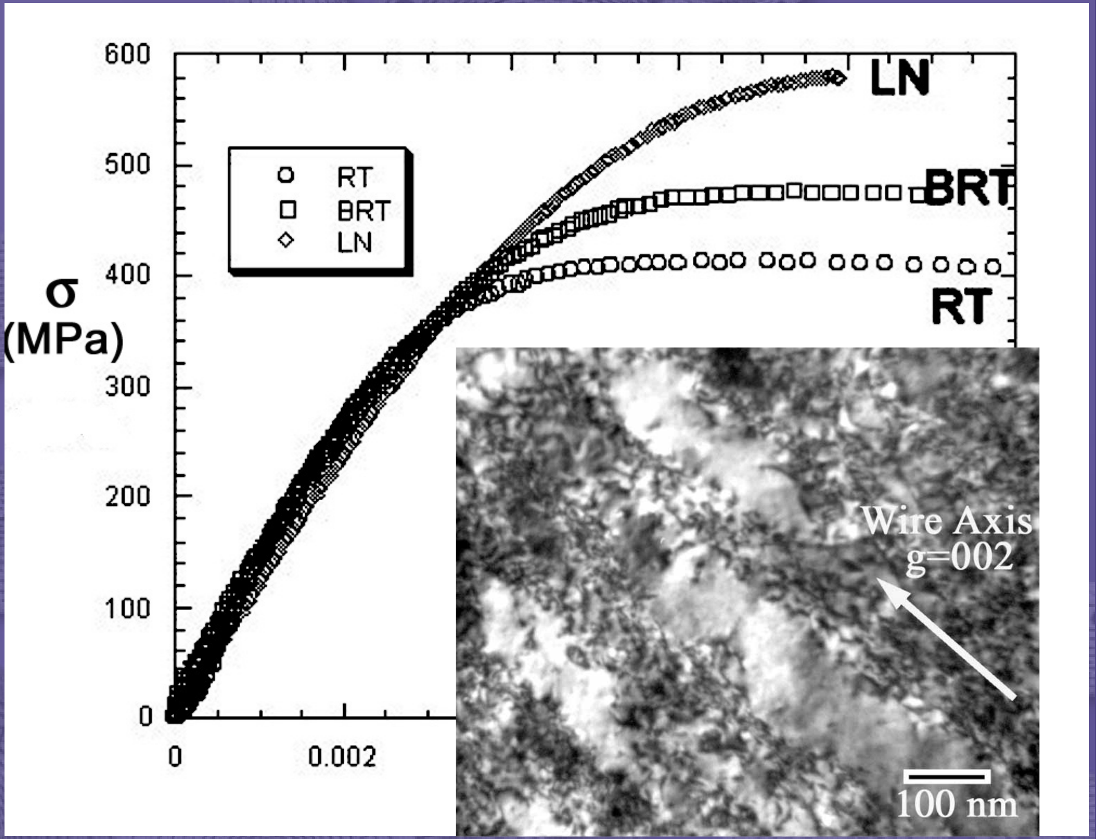
- *Annealed pure Cu is a fcc metal with electrical resistivity* < 1.74μΩ·cm or higher than 100% International Annealed Cu Standard (IACS)
  - *When yield, dislocations start to move or to be generated*
  - *To increase the strength, one needs to increase the density of obstacles t dislocation motion*
- *Generation of dislocations: room temperature deformation makes Cu to reach strength greater than 400 MPa*
- *At room temperature (RT), deformation can only introduce a limited number of dislocations in pure metals due to dislocation annihilation.*



TEM image of samples deformed at RT to strain of 2.5 (the thin foil was sectioned perpendicular to the drawing direction in the centre of the wires.

Strengthening Cu by high density of dislocation and twins

- *Increased density of dislocations can make Cu with strength much greater than 400 MPa*
  - *RT limitation is expanded by a cryogenic deformation*
  - *Cryogenic deformation permits accumulation of both nanotwins and a high density of dislocations.*
  - *Cryogenic deformation produces bulk pure Cu with a yield strength about 1.5 times that of RT-deformed Cu.*
  - *RT resistivity increase is < 5% by generation of dislocations*
- *High density of twins can also be produced by deposition and other technologies*

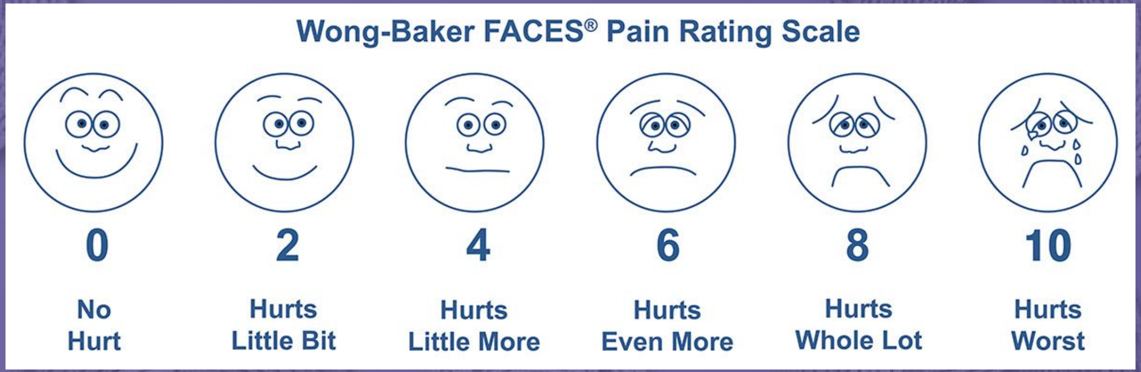


Comparison of the RT true stress versus strain curves for pure Cu deformed to a strain of 2.3 at different temperatures. RT, BRT and LN indicate room temperatur below room temperature and liquid nitrogen temperatu deformations.

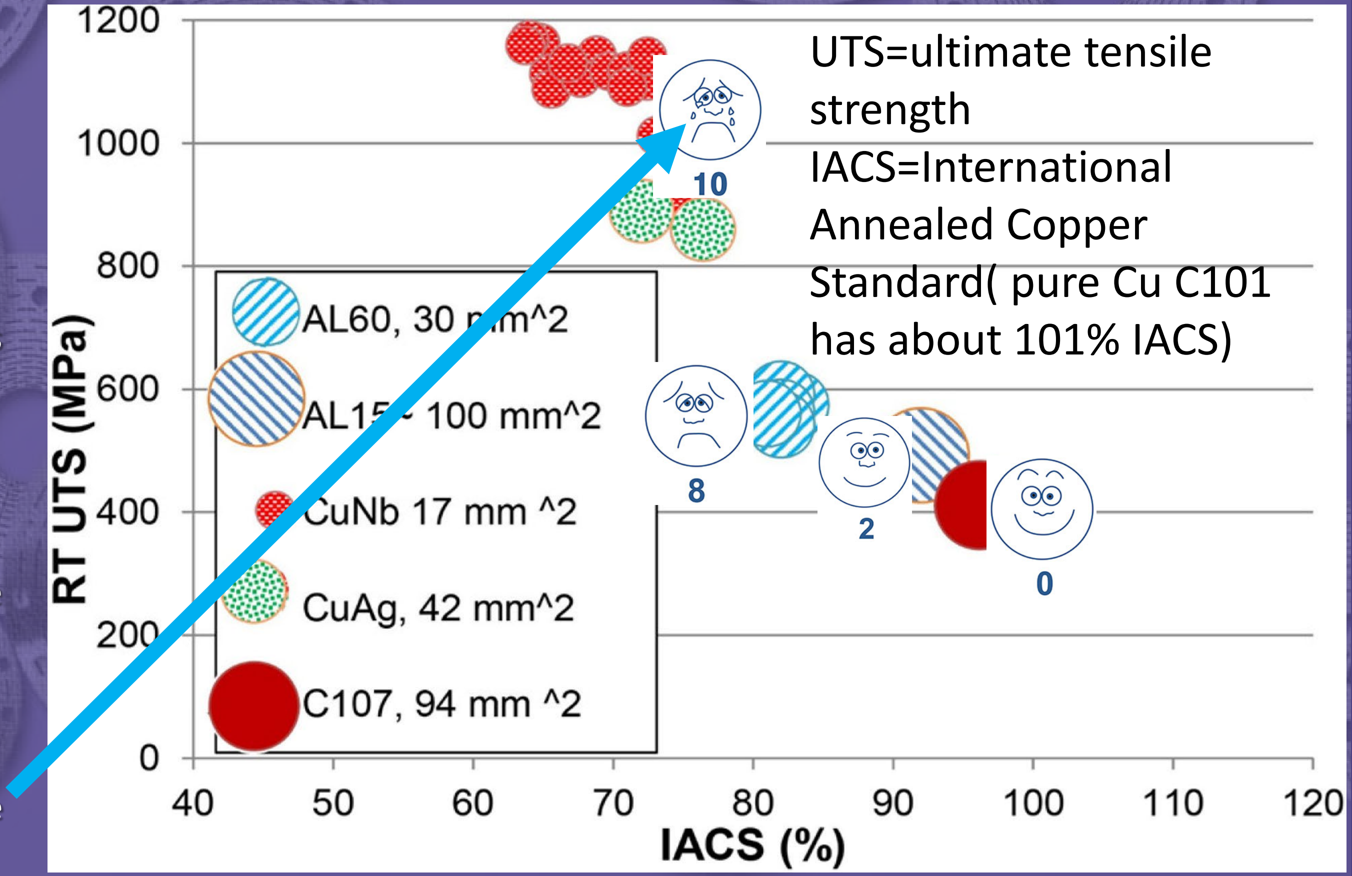
Inset: TEM dark field image of a LNT deformed sample

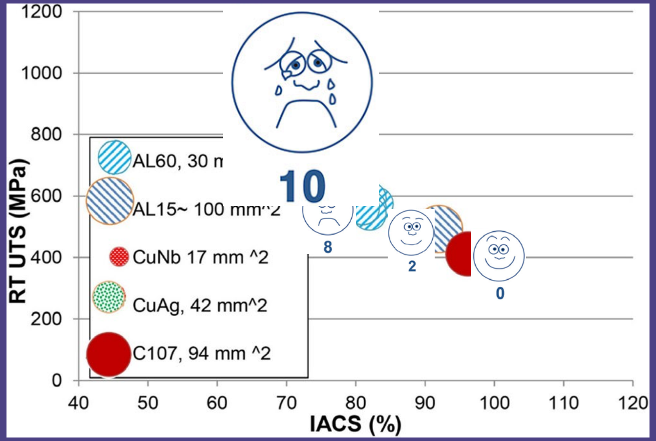
Property and fabrication chart for Cu based alloys and composites

Most of conductors described here are suitable for coils in the 100 T pulsed magnet and for the 45 T resistive magnet operated in MagLab. We used the familiar pain-rating scale to indicate the relative difficulty of making each conductor



- C107 , a Ag bearing Cu, is rated “zero” in the pain chart, indicated that it is relatively easy to make
- AL15, a Cu matrix composite with low alumina content, is rated “two” (hurts little bit), indicating that it is not as easy to make as C107
- AL60, a Cu matrix composite with high alumina content, is rated “eight”(hurts a whole lot), indicating that it is *much* more difficult to make than AL15, even though it is only little stronger
- High strength CuAg, which is used in resistive magnets, would perhaps be rated “nine,” is one of the most difficult conductors to make
- CuNb, which is mainly for insert, is rated “ten,” extremely difficult to make



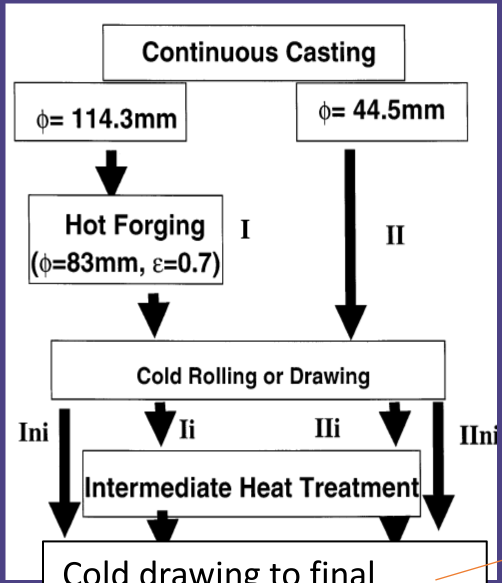


Possible fabrication routes for High-strength conductor wires

In-situ composite

Induction or arc-melted Cu–X (x=Ag or Nb) ingots: Cu matrix containing X dendrites,

Casting-forging-cold drawing

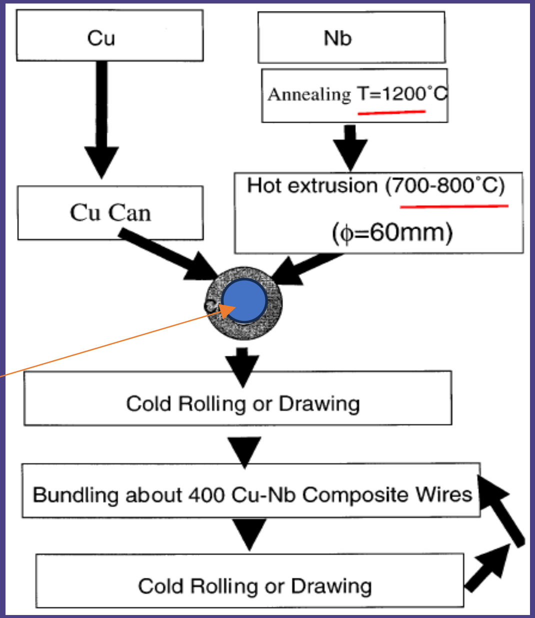


Cold drawing to final dimensions or to intermediate composites

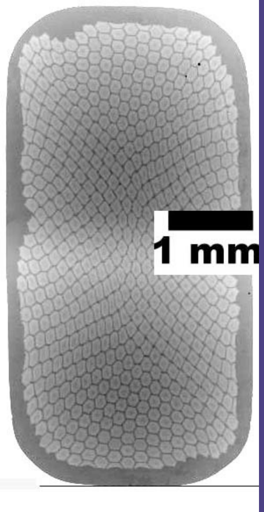
Continuous composite

bulk Cu tubes and X(x=Nb, Ta) or Cu-X rods:
Cu matrix containing Nb continuous filaments

Bundling-hot extruding-cold drawing



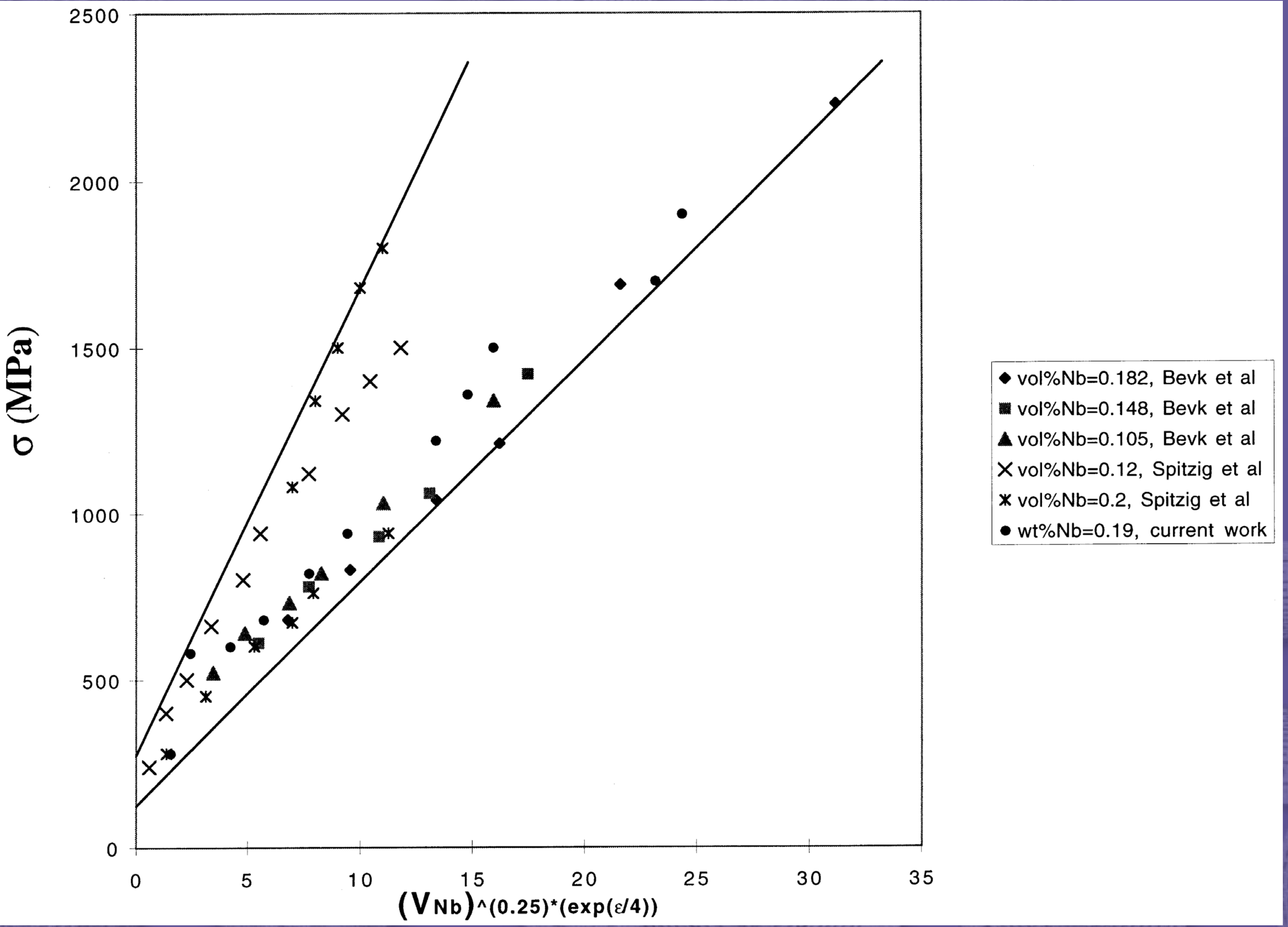
Cu-X or Nb



SEM cross-sectional image showing microstructure of 3x5.8 mm CuNb wire. The wire is composed of sub-elements that are composed of many nano-Nb ribbons

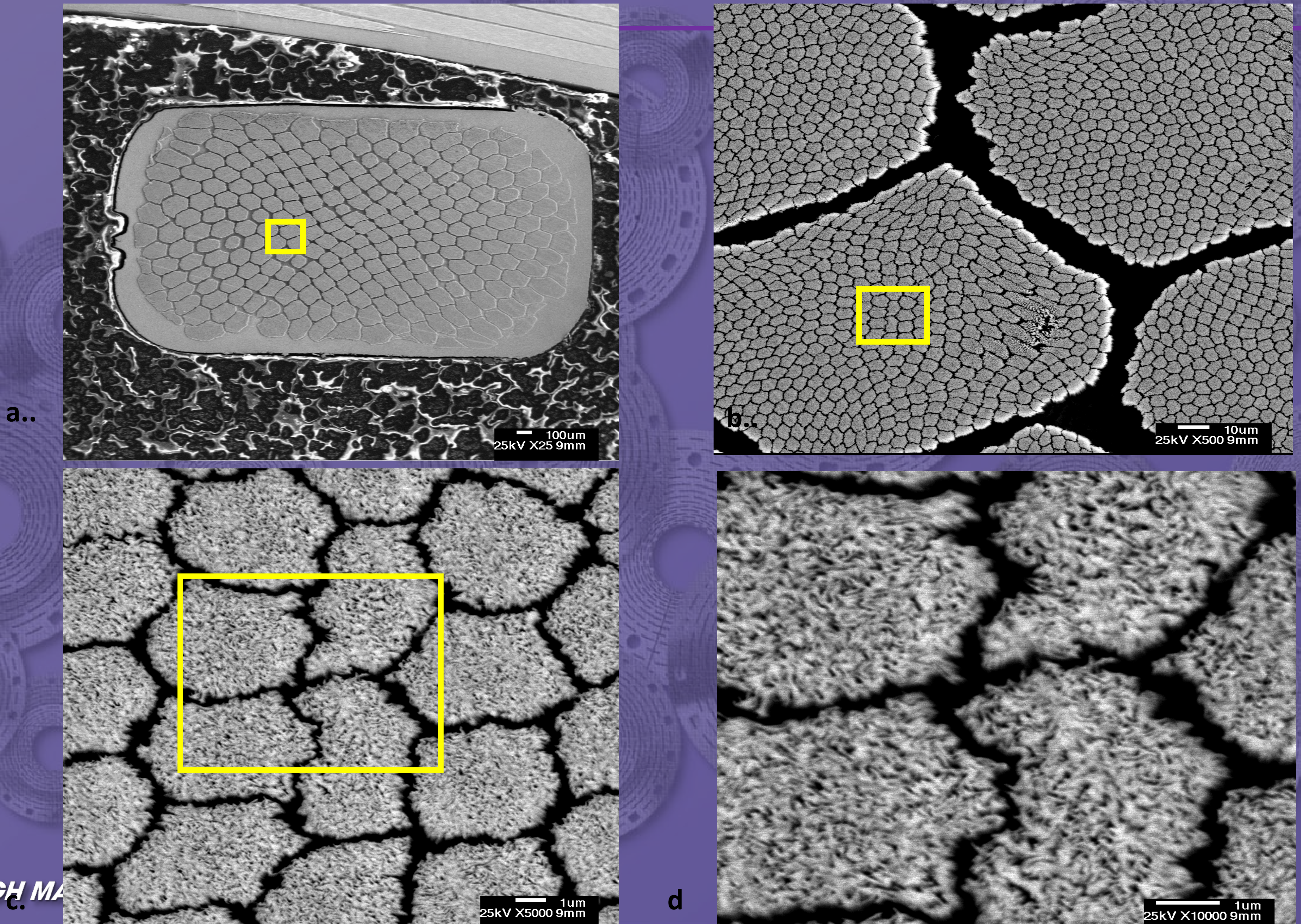
Cu-Nb: One of the conductors with high strength

1. **Cu-Nb achieved very high mechanical strength**
   - ➢ High strength needs very fine structure.
   - ➢ Fine structure may reduce electrical conductivity
2. **High strength needs very large deformation strain if the strength is achieved by deformation**
   - ➢ High strength only achievable in a very small cross-section area.
   - ➢ Magnet needs cross-section greater than 10 mm^2.

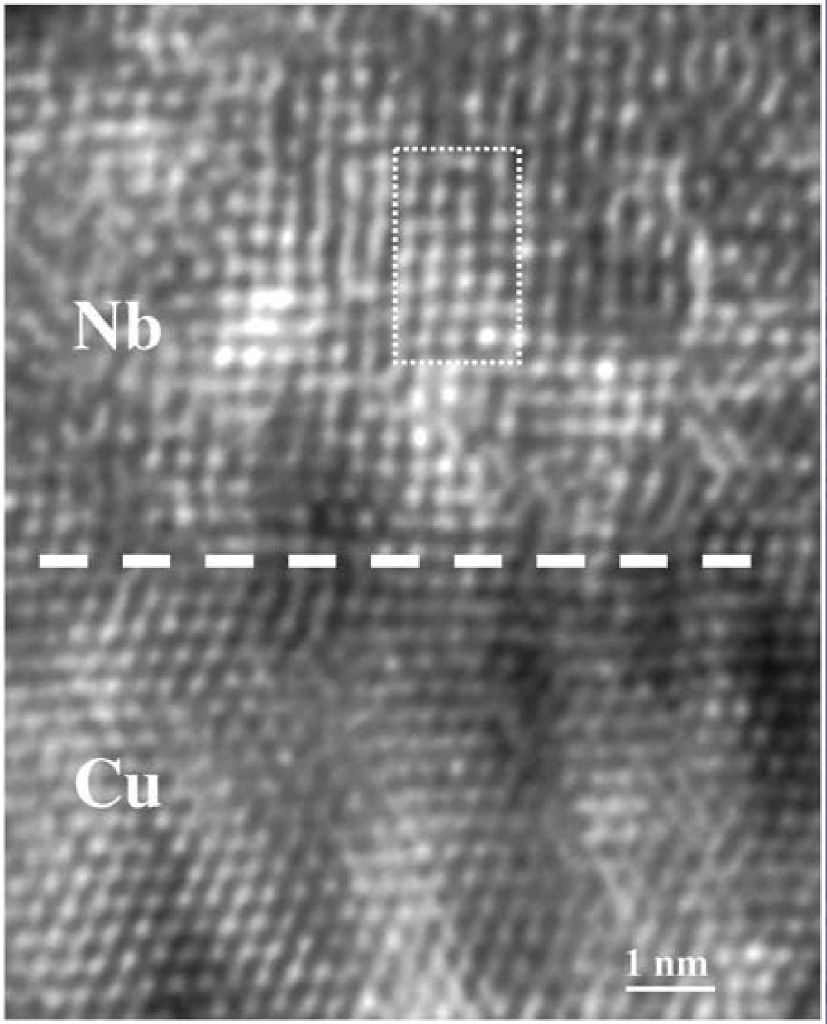


Summary of the dependence of tensile strength on deformation of strain of Cu–Nb composites normalized with vol% of Nb.

SEM images showing the hierarchical structure of Cu-Nb Nanostructured composite

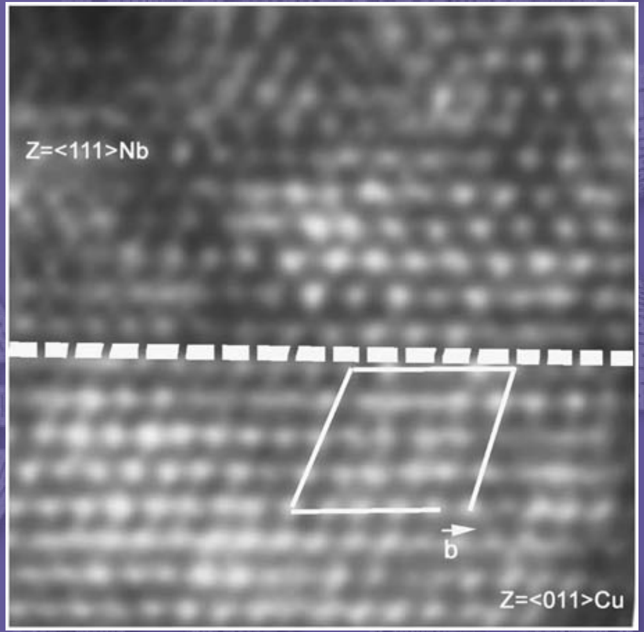


Distorted Nb in Cu



- *Interfaces are relatively sharp when spacing between Nb reaches 10 nm (dotted line in left image)*
- *Locally distorted zones are observed*
- *Cu and Nb have an orientation relationship*
- *Dislocation density is not very high*
- *Internal stresses exist*

b..

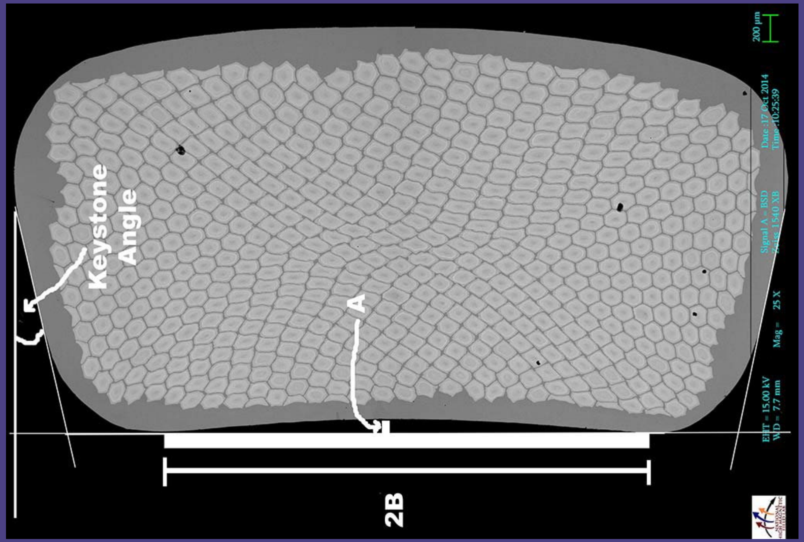


An HRTEM image taken close to an interface (marked by a dotted line) showing a circuit n the Cu layer defining a dislocation with a Burgers vector in the 211 direction.

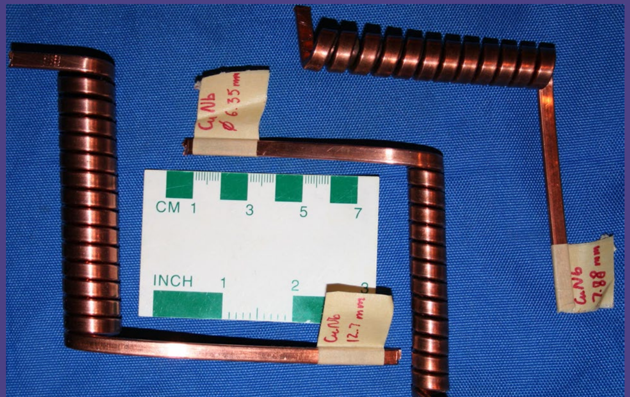
c. d

Properties vs Microstructure

- *In addition to interface spacing, the macroscopic properties are determined by*
  - *Short wave-length internal stresses*
  - *Reduced dislocation densities due to refined interface spacing*
  - *Overall texture of the Cu matrix-anisotropy of properties*
  - *Local orientation-relationship between the strengthening component and the matrix*
  - *Dissolution of the second component in the Cu matrix because of the refinement of microstructure*
- *Deformation by coil winding*
  - *Complex internal stress status*
  - *Deformation inhomogeneity*



SEM cross-sectional image showing a keystone-shaped wire after the wire with sufficient ductility was wound into a small diameter coil . Large bending strain was found in those wires. The ductility was optimized by heat treatment that engineers internal stresses.



Remarks

- Varied magnet coil requirements:
  - Different magnet coils necessitate diverse conductors.
  - Tailored conductors are essential to meet specific size and performance criteria.
- Composite Conductor Manufacturing:
  - Cu-Nb composite conductors pose significant manufacturing challenges
  - Cu-Ag composite conductors needs less deformation strain to achieve the same strength level of Cu-Nb
  - Achieving desired size and properties demands advanced techniques and processes.
  - Continuous development is crucial to meet materials parameters.
- Attaining higher magnetic field strengths requires ongoing innovation and refinement.

a..

b..

c.

d