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Searching for high strength, high electrical conductivity, and high thermal stability of Cu and Cu alloys…

Yinmin (Morris) Wang), ymwang@ucla.edu

Professor
Department of Materials Science and Engineering
University of California, Los Angeles
410 Westwood Plaza, Engineering V
Los Angeles, CA, USA

Key property requirement of copper and copper alloys for normal-conducting radiofrequency (RF) cavities

- Electrical Conductivity: High electrical conductivity minimizes power losses and ensures efficient acceleration of the beam (C10100 – OFE Cu, 100% IACS).

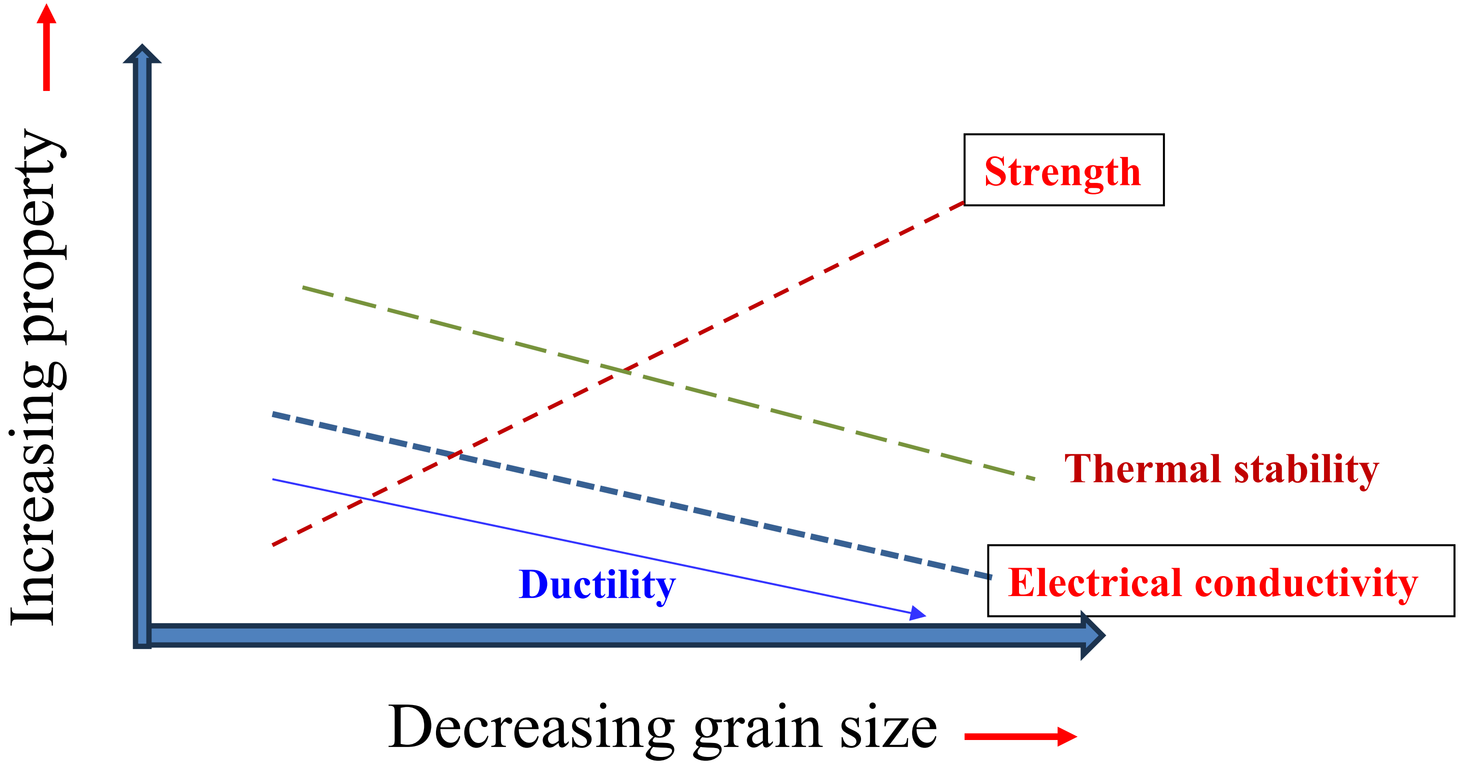
- Thermal Conductivity: High thermal conductivity is critical for dissipating the heat generated by RF power and beam interactions, thus maintaining the structural integrity.

- Mechanical Strength & Hardness: Accelerator components experience mechanical stress from thermal expansion and electromagnetic forces. Materials with high mechanical strength and hardness resist deformation and maintain the precise geometry of the cavities (C15715 – Cu+0.3wt% Al_2O_3; CuCr1Zr).

- Resistance to Radiation Damage: In high-energy accelerators, materials are exposed to intense radiation, making resistance to radiation-induced degradation essential for longevity and reliable operation.

Strength and electrical conductivity are tradeoff variables in materials science.

Structure-property relationship of nanostructured copper



Tensile strength vs electrical conductivity of Cu and Cu alloys

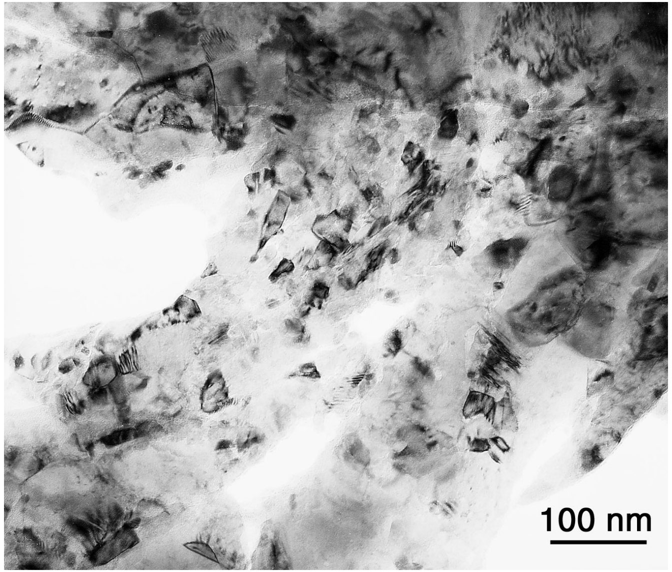
This figure is removed due to the proprietary information.

Similar tradeoff exists between tensile strength and thermal conductivity

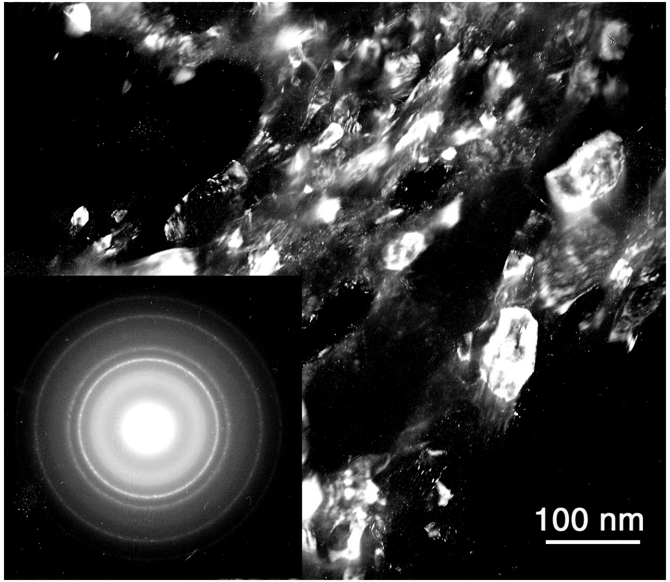
Methods to make strong nanocrystalline/nanotwinned Cu

1. **Electroplating** (organic additives, H, S)
2. **Magnetron sputtering**
3. **Gas phase condensation + consolidation** (pores)
4. **Nanocrystallization from amorphous precursors**
5. **Severe plastic deformation**
   - Equal channel angular pressing (ECAP)
   - Surface mechanical attrition (SMA)
   - Surface wearing
   - Cold rolling
6. **Additive manufacturing (powder based)**

TEM Micrographs of surface mechanical attrition prepared Cu
(taken at 14 μm underneath the surface)



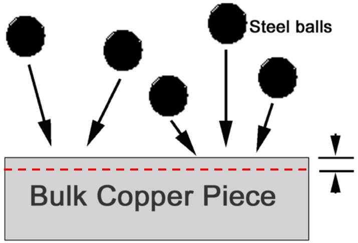
(Bright Field)

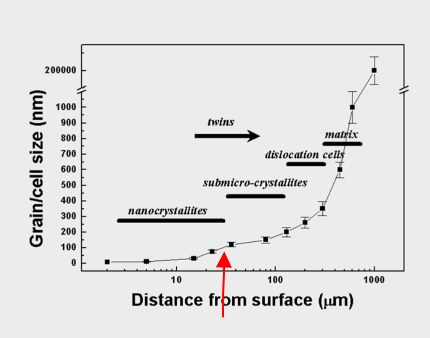


(Dark Field)

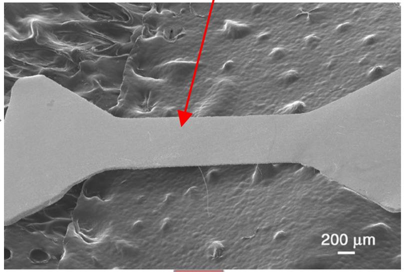
Scr. Mater. 48, 1581-1586 (2003).

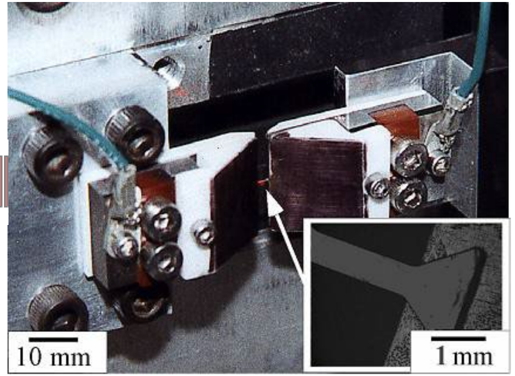
Is nanocrystalline copper ductile?

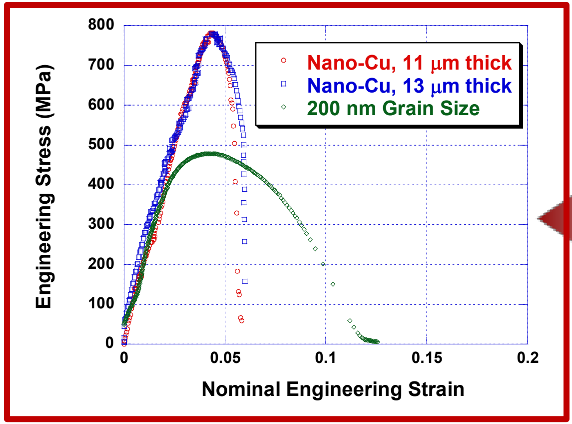




(10-15 μm thick)







Nanocrystalline Cu (30nm) is rather brittle; but has clear plasticity!!!

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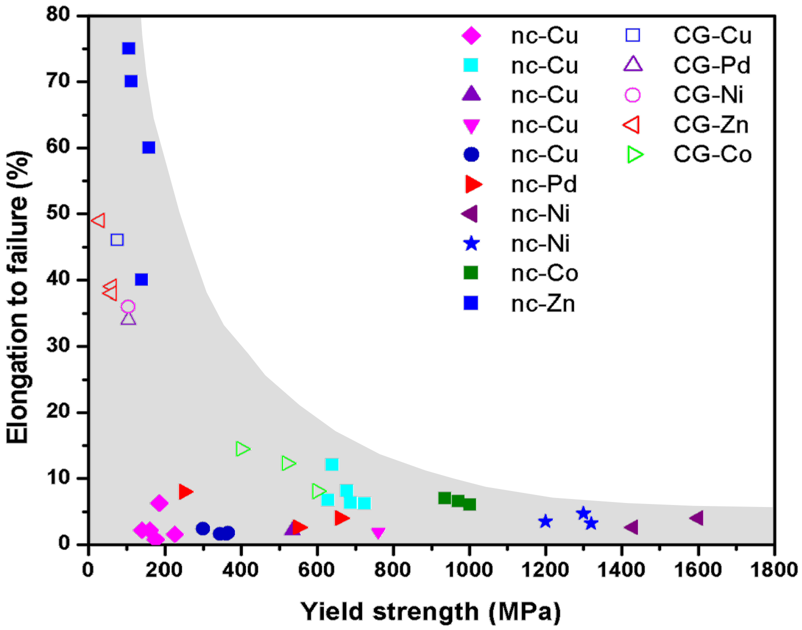
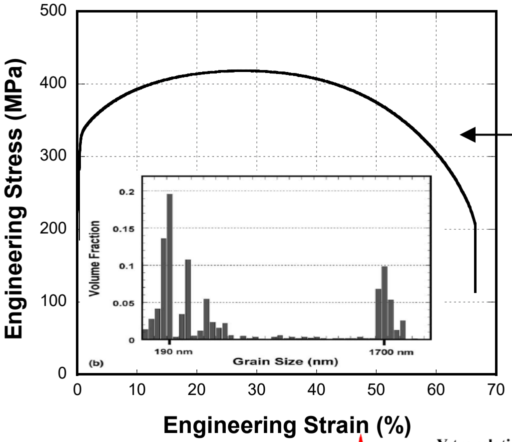
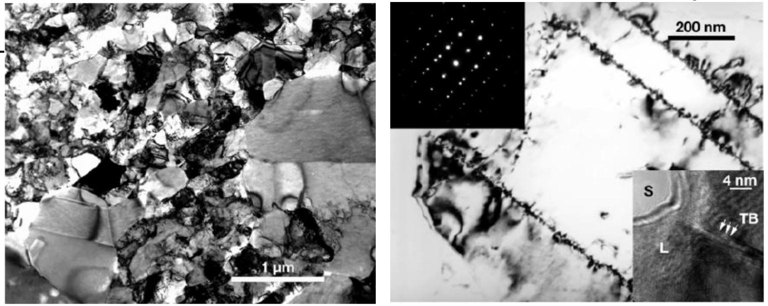
Strength - ductility tradeoff trend in pure nanocrystalline metals



Increase work hardening using bimodal grain structure

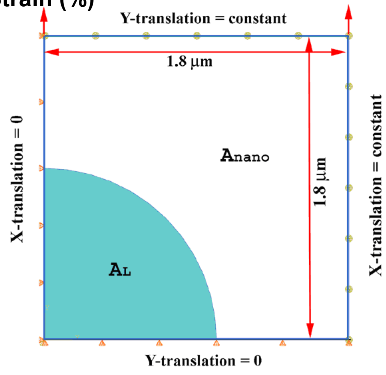


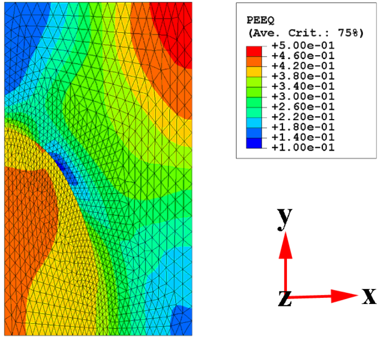
Bimodal structure leads to new deformation mechanism and good mechanical property



Nature 419, 912 (2002).

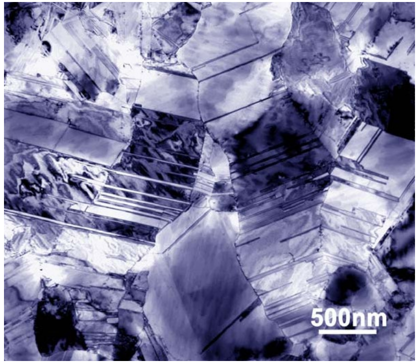
Also see bimodal structure developed in nano-Al alloys (Lavernia, UC Irvine)

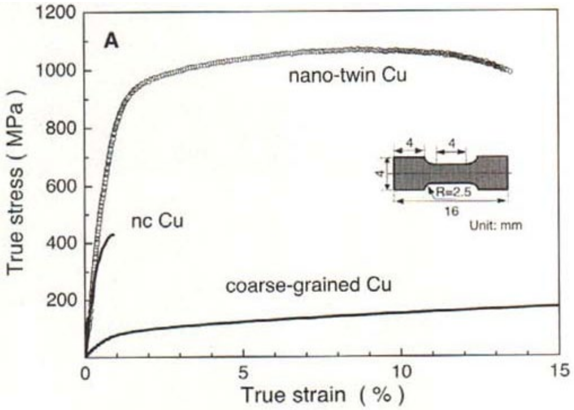




High strength, high electrical conductivity nanotwinned Cu

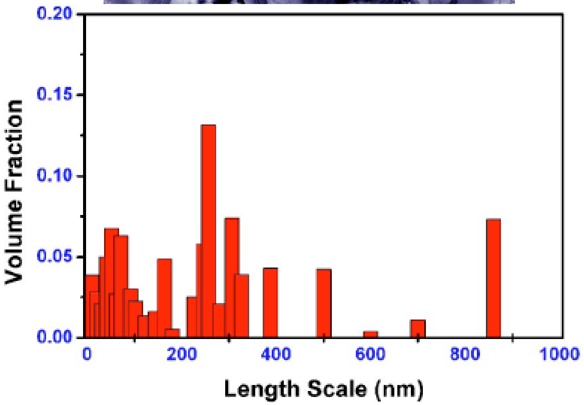
Electrodeposition



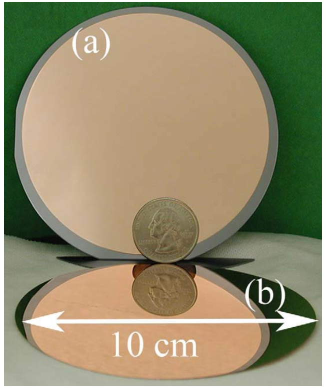


97% IACS

Lu et al., science 304, 422 (2004).
Wang et al, Appl. Phys. Lett. 85, 4932 (2004).



Multi-scale microstructure distribution



Hodge, Wang, Barbee, Mater. Sci. Eng. A 429, 272 (2006).

Magnetron sputtering

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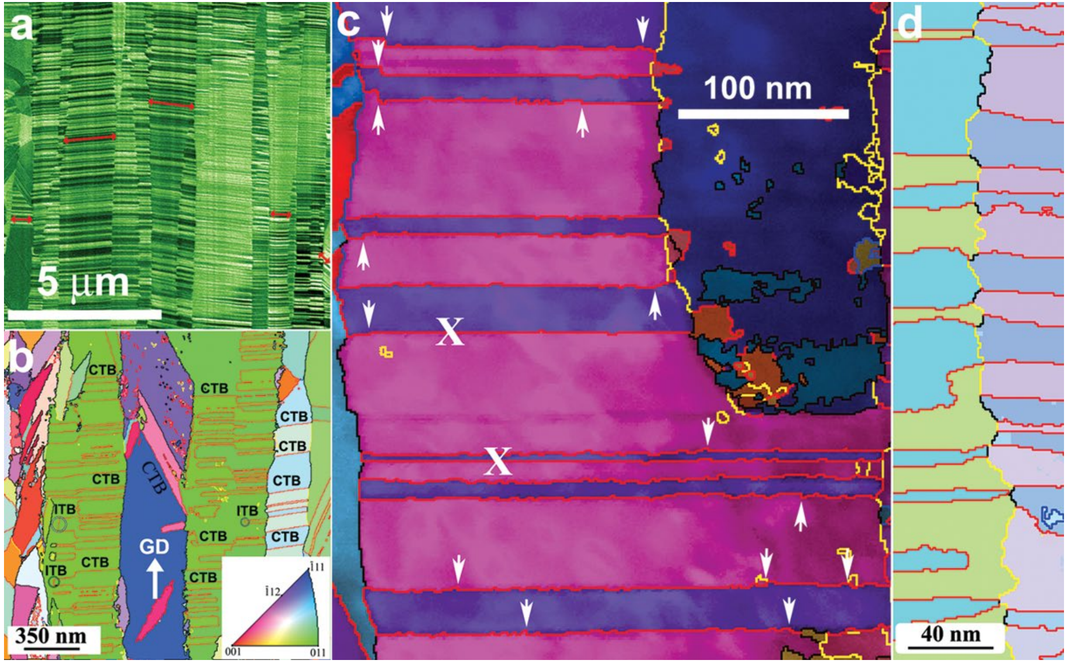
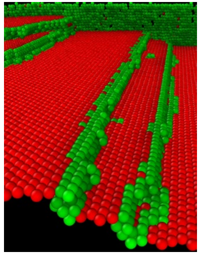
Nanotwinned copper

This figure is removed due to the proprietary information.

Challenge: twin density is difficult to scale to the component level.

Thermal stability: defective twin boundaries in nanotwinned Cu





Inverse pole figure orientation mapping in TEM

~1nm spatial resolution and ~1 degree misorientation.

Nat. Mater. 12, 697-702 (2013).

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Kink migration mechanisms affect thermal stability

Tensile direction

Tensile direction

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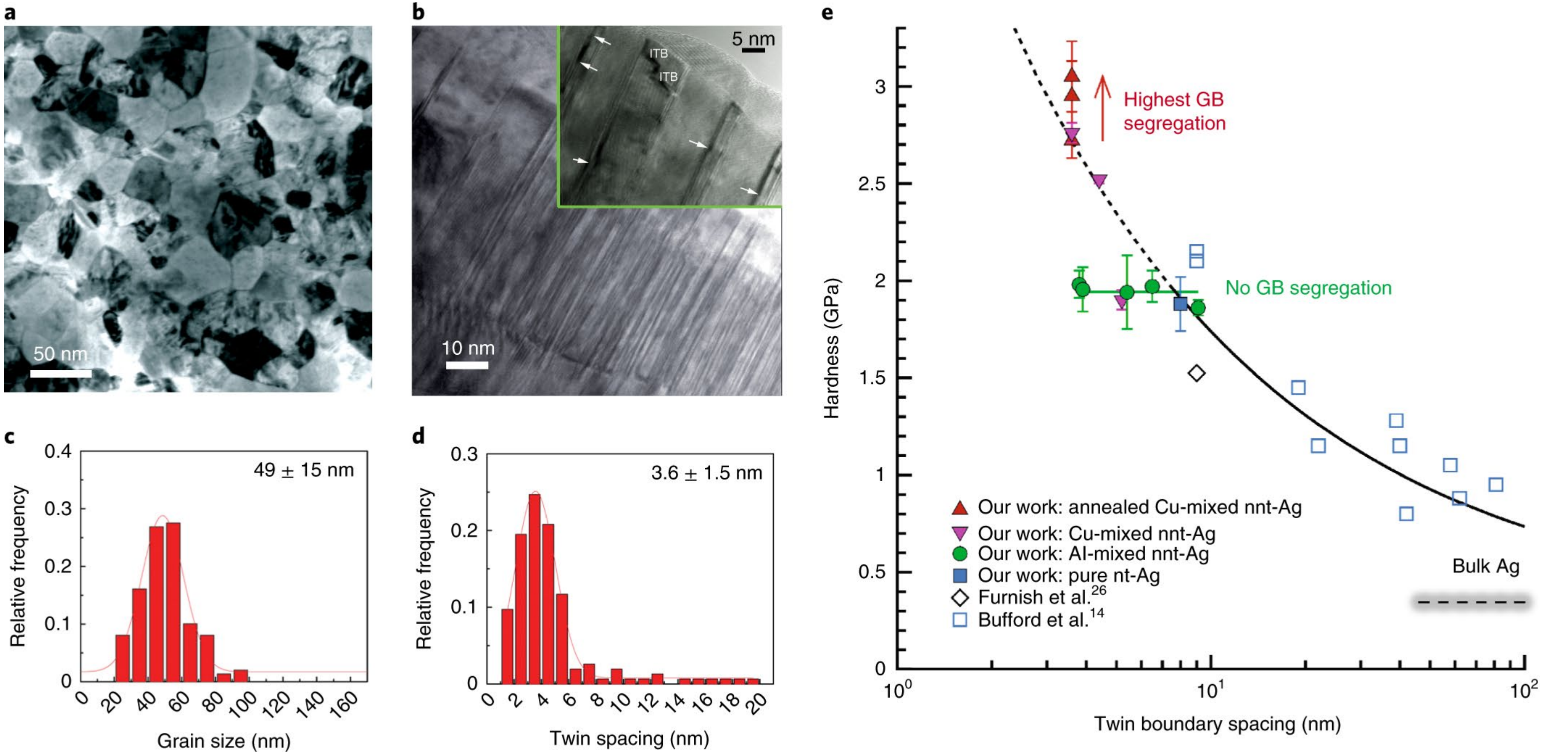
Nanocrystalline-nanotwinned (nnt) Ag, doped by selected elements (Cu, Al, Ni, etc.)



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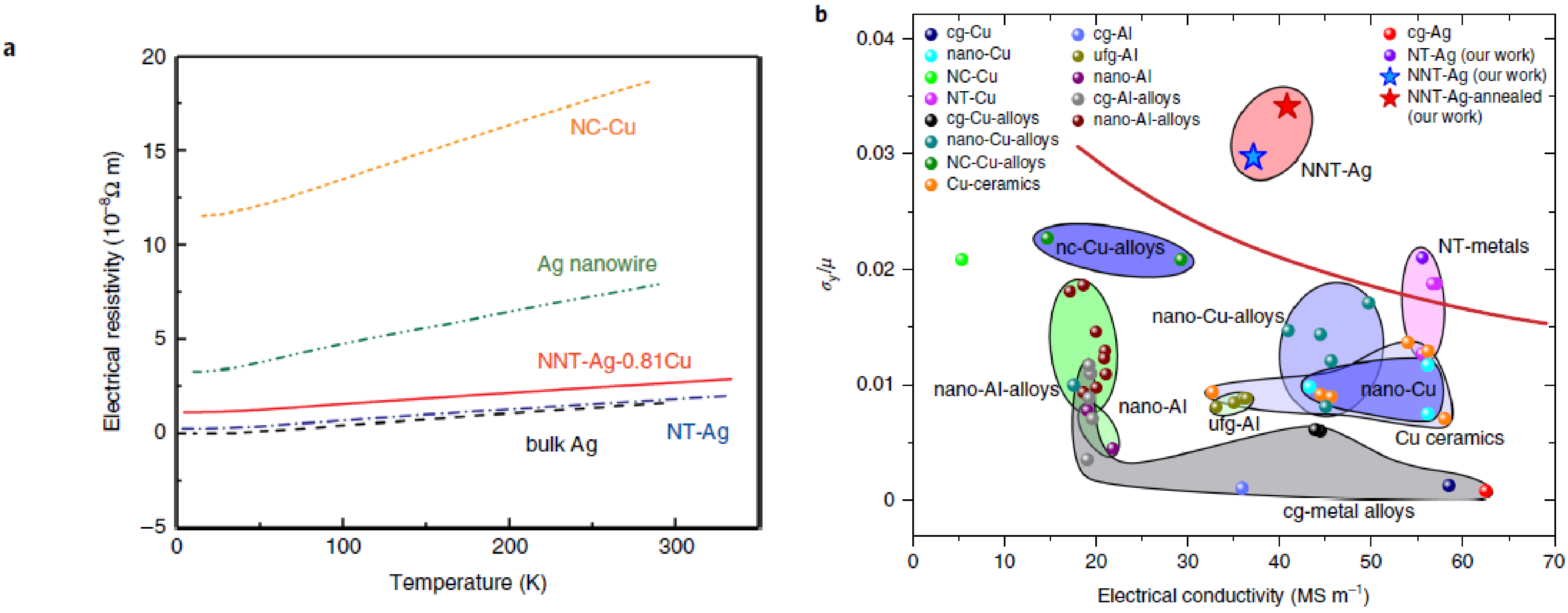
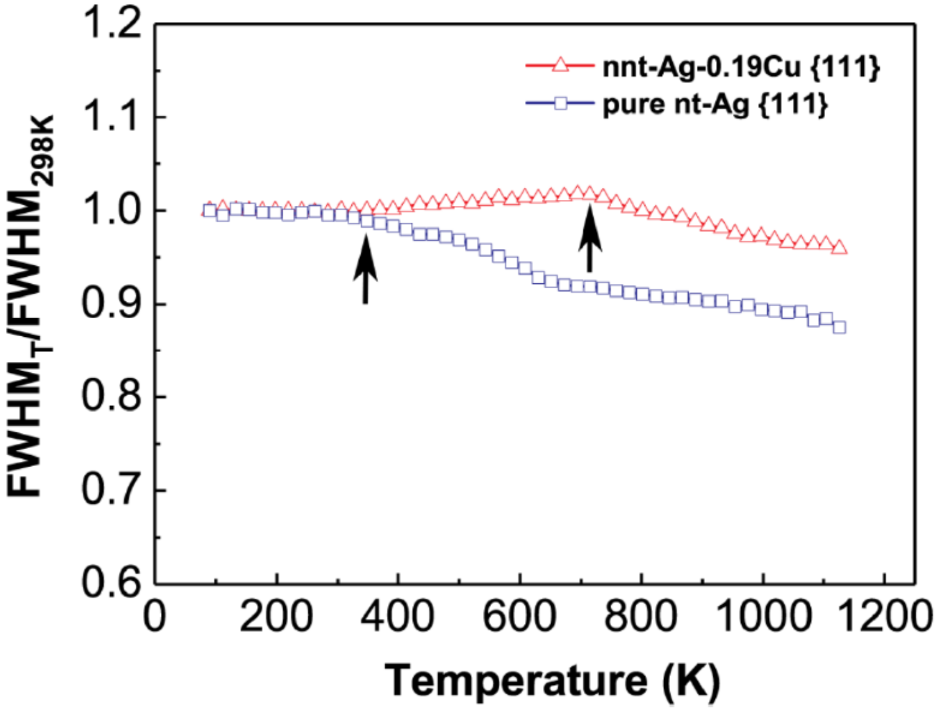
Nat. Mater. 18, 1207-1214 (2019).

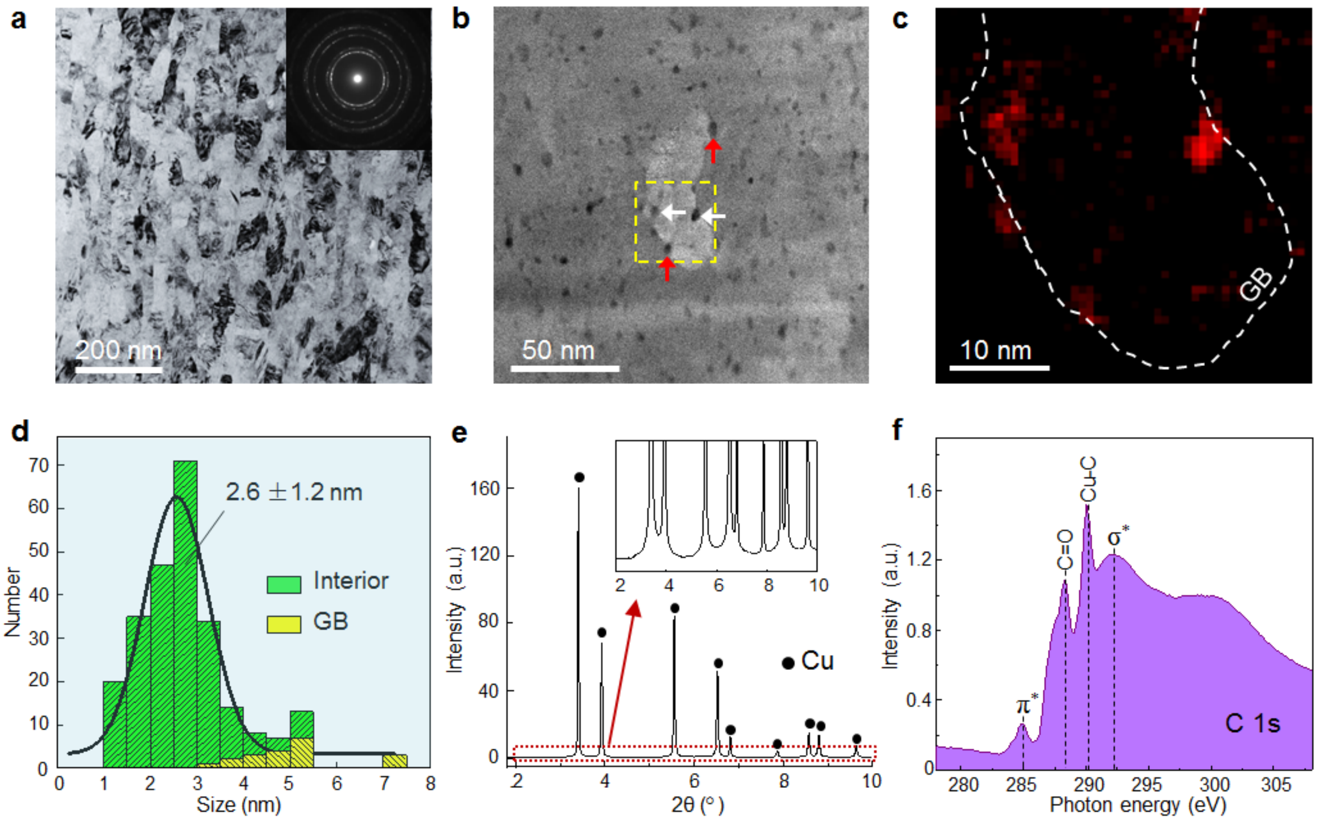
Strength – electrical conductivity synergy in nnt-Ag



The thermal stability is increased by 225K



Ultrastrong and thermally stable nanocrystalline Cu doped by graphene nanoparticles



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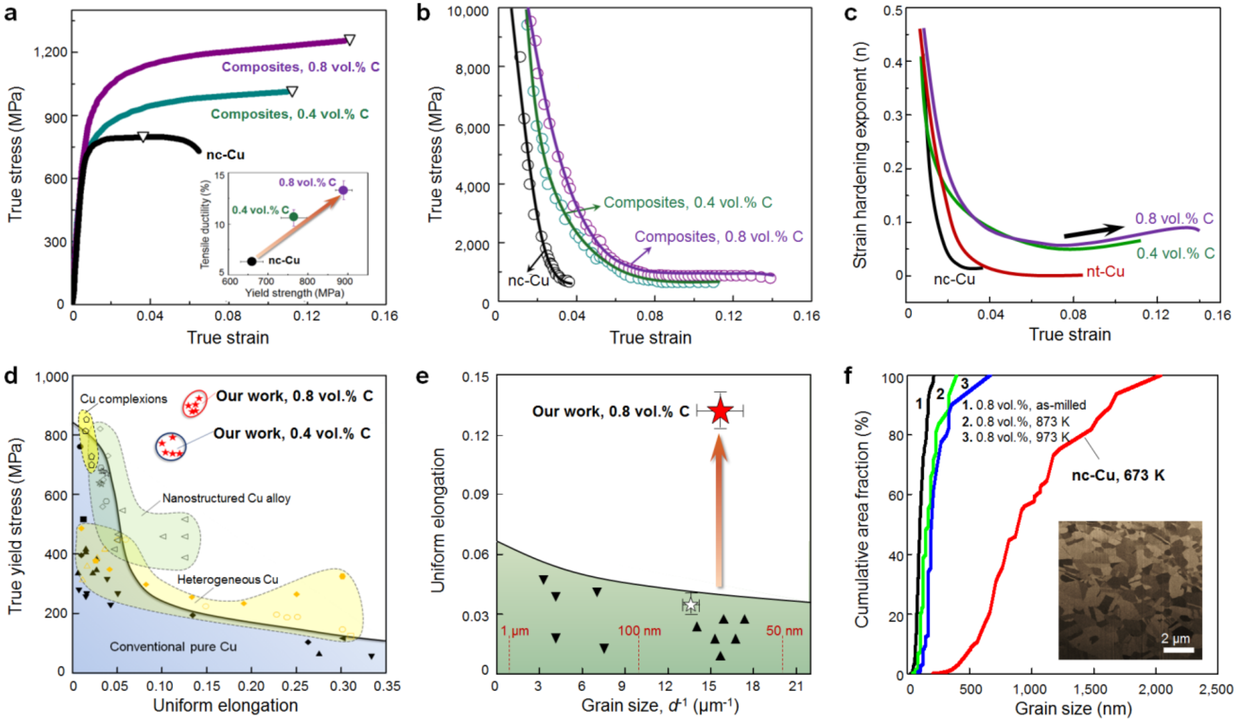
The ultimate tensile strength of Cu >1.2 GPa



Nat. Commun. 13, 5581 (2022).

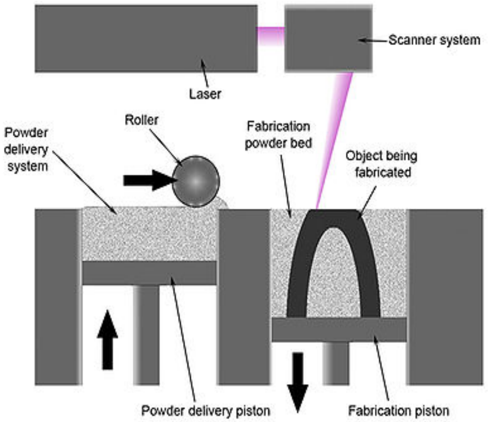
Electrical conductivity: 42 MS/m (72% IACS).

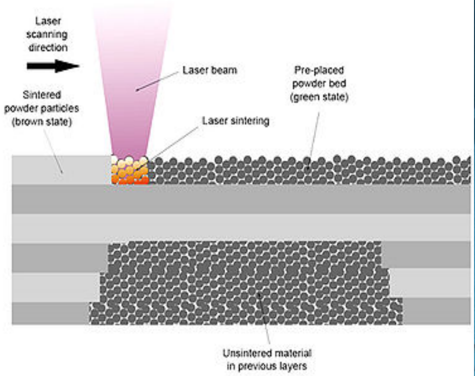
Where are we for graphene-doped nanocrystalline Cu?

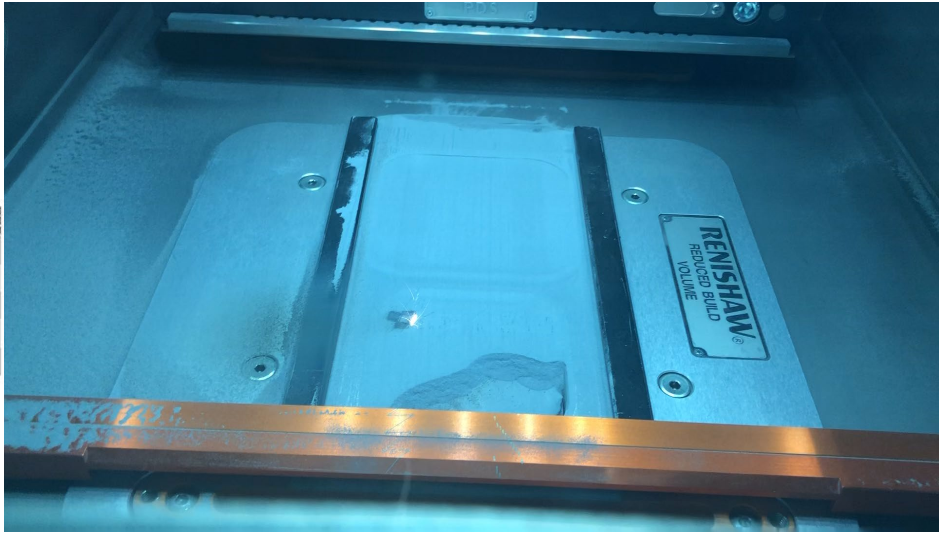
This figure is removed due to the proprietary information.

Challenge: scale up

Laser powder-bed-fusion of copper?



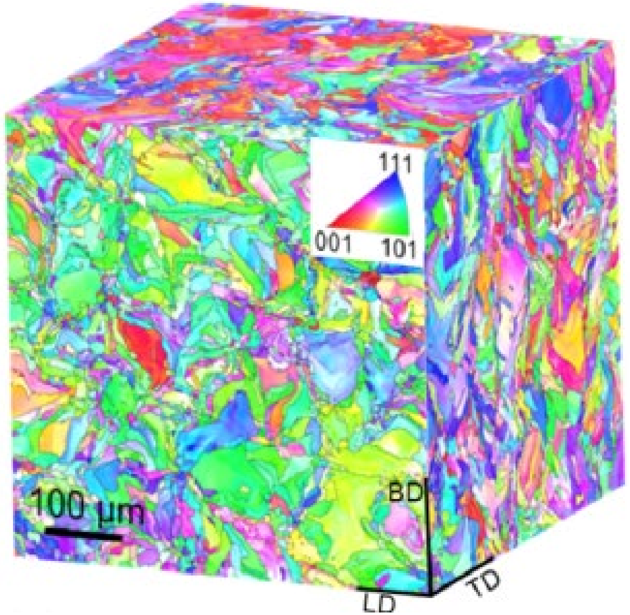


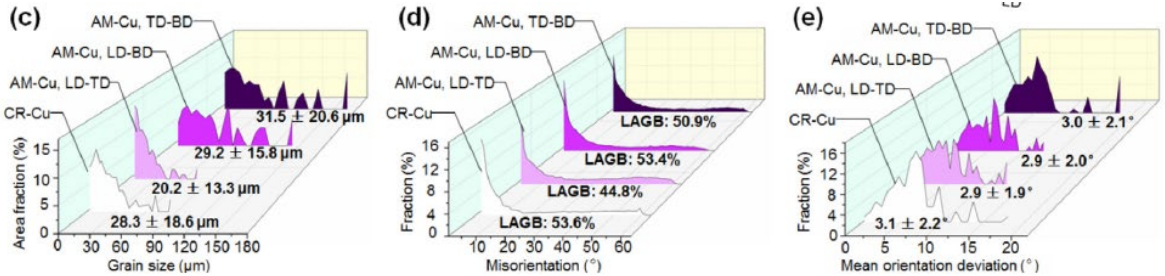


Laser powder-bed-fusion

The length scale in L-PBF pure copper

(a)





Observations:

- The grain sizes defined by high angle grain boundaries are large (beneficial for ductility).
- The fraction of low angle grain boundaries is high (>50%).
- No chemical cells. Dislocation cells exist, the size of which is much smaller than the grain size.

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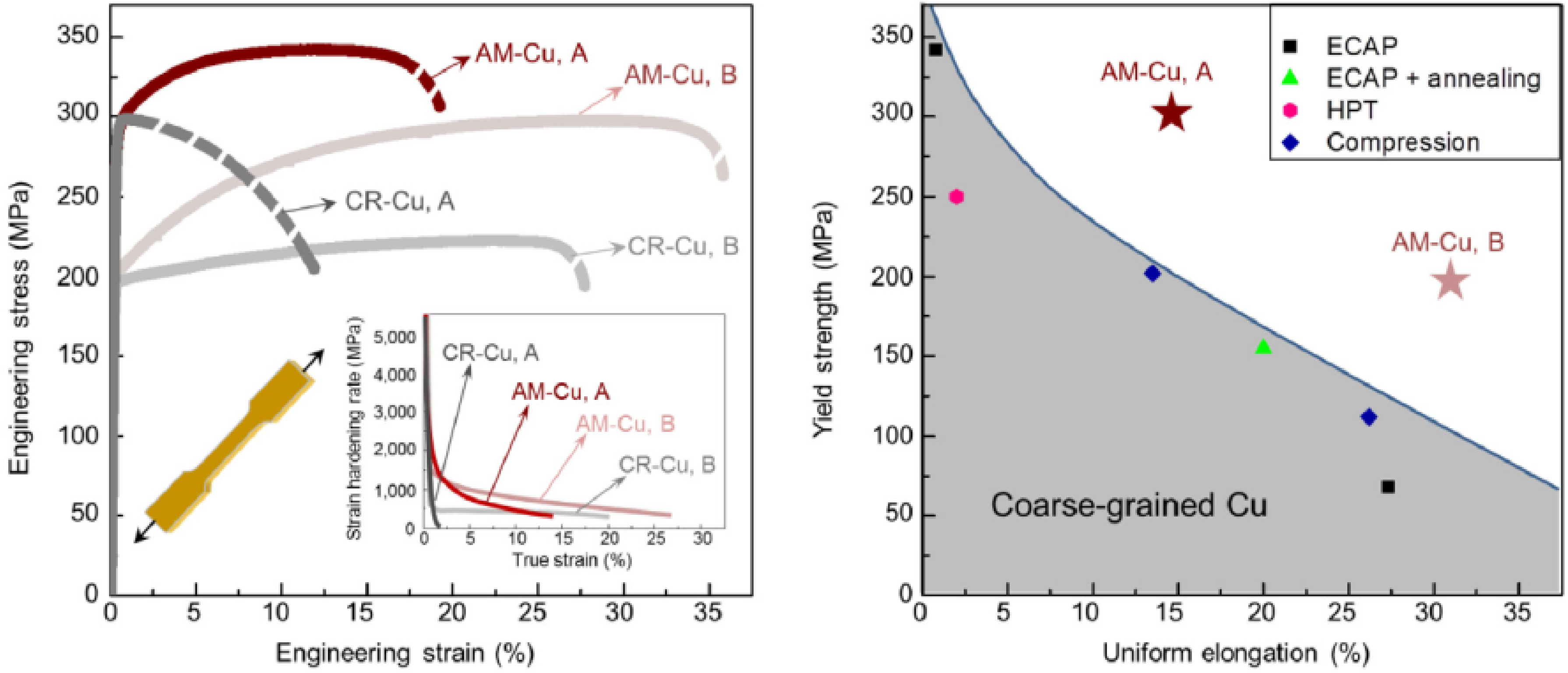
Strength-ductility combinations of L-PBF Cu



Mater. Today 50 (2021) 79-88.

Strength and electrical conductivity of L-PBF copper

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Summary

- Nanocrystalline or nanostructured copper (with high strength) will not work for RF cavity applications. Playing with grain boundary distribution (bi- or tri-modal grain size distribution may offer better properties).
- Strategies have been developed over the years to achieve high strength, high electrical conductivity copper. However, most of these strategies do not consider other physical properties (thermal stability, radiation resistance, etc.). Doping or composites may be a good recipe to achieve multi-functional properties in copper.
- Additive manufacturing has just started to work its way into copper structure/component fabrications and may offer a scalable approach for novel copper materials.

Q&A