Mechanical alloying and amorphization in Cu-Nb-Ag in situ composite wires studied by TEM and atom probe tomography

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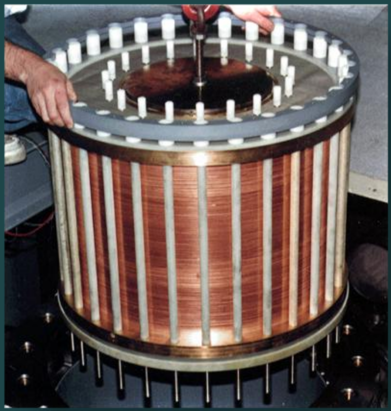
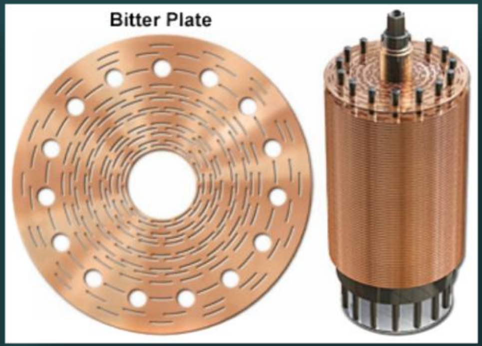
Übersicht

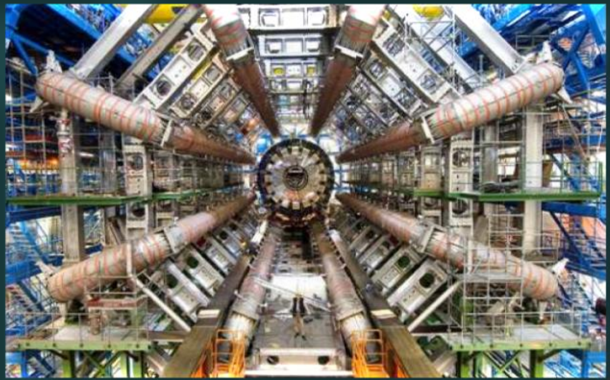
- Motivation and Methods
- Results
- Discussion
- Outlook and open questions

Motivation: High strength resistive conductors

- High strength electrical conductors: Multiphase materials; here: Cu-5 at.% Ag-3 at.% Nb (Cu-8.2wt%Ag-4wt%Nb) in-situ composite
- Co-deformation mechanisms at large strains (mechanical alloying; phase dissolution; dislocations in confined geometries; hetereophase dislocation transmission; amorphization; conductivity)
- Melt, cast, wire; SEM, TEM, APT

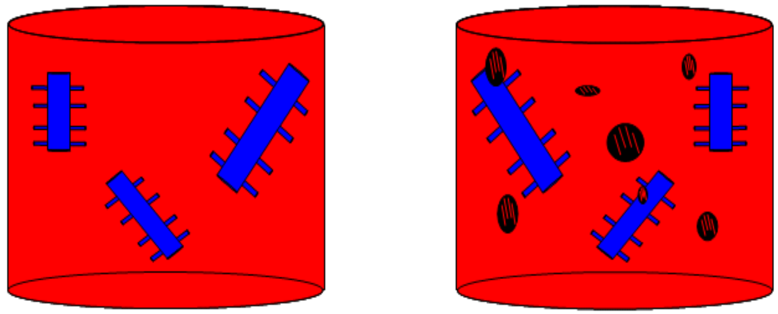




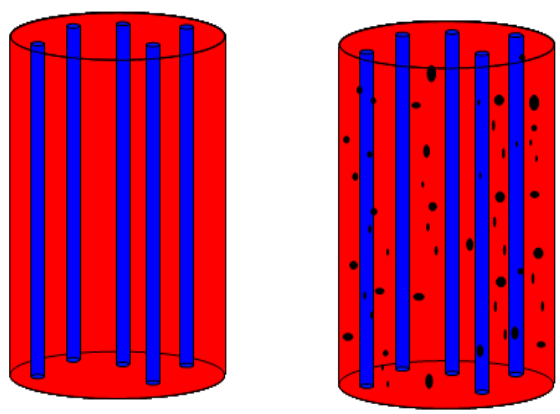


Raabe, Mattissen: Acta Mater 46 (1998) 5973

Nb
Ag/Cu
Cu



binary ternary



nm-spacing:
high strength
low scattering

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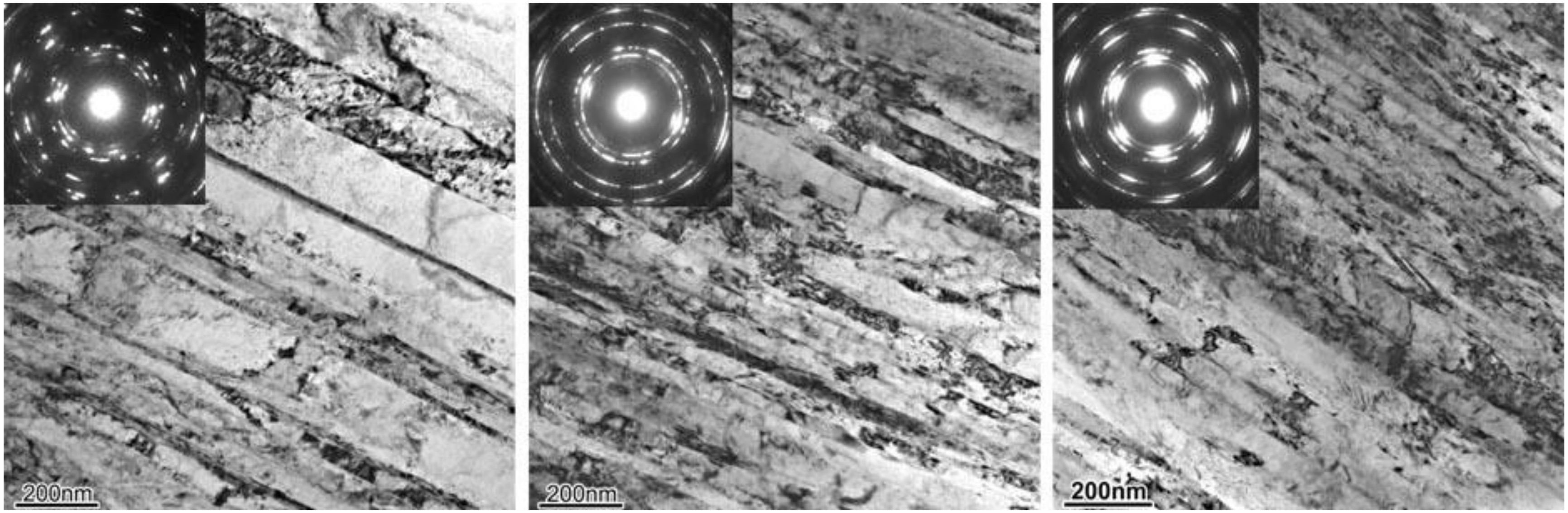
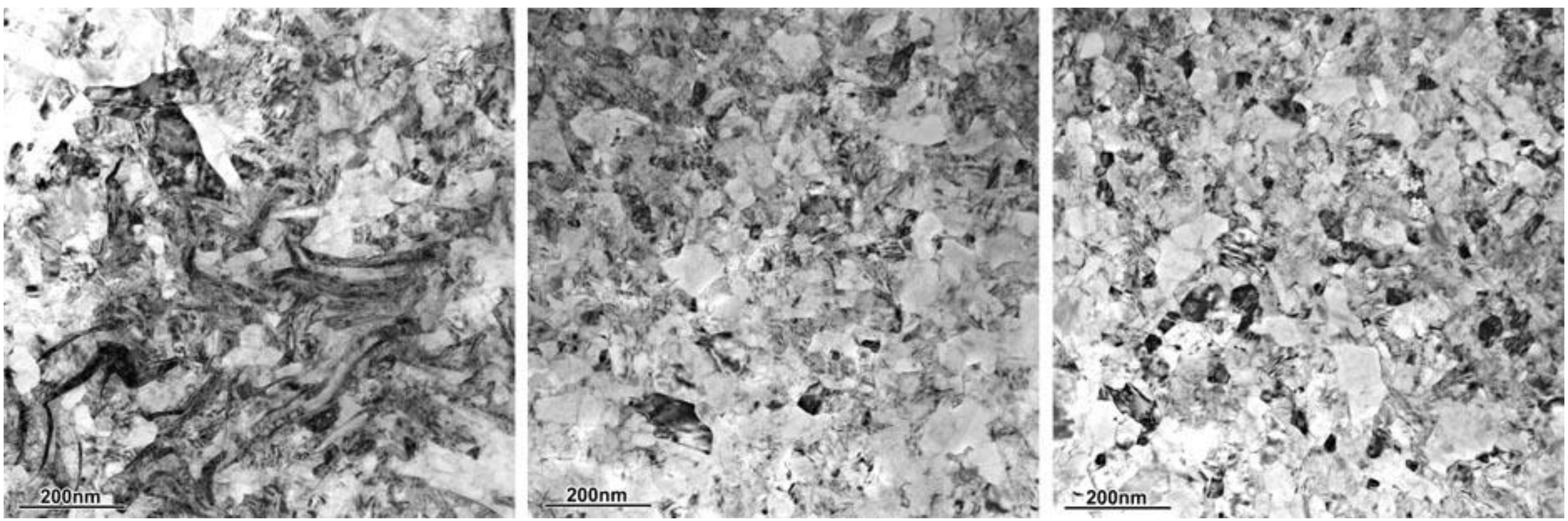
D. Raabe: Advanced Materials 14 (2002) p. 639

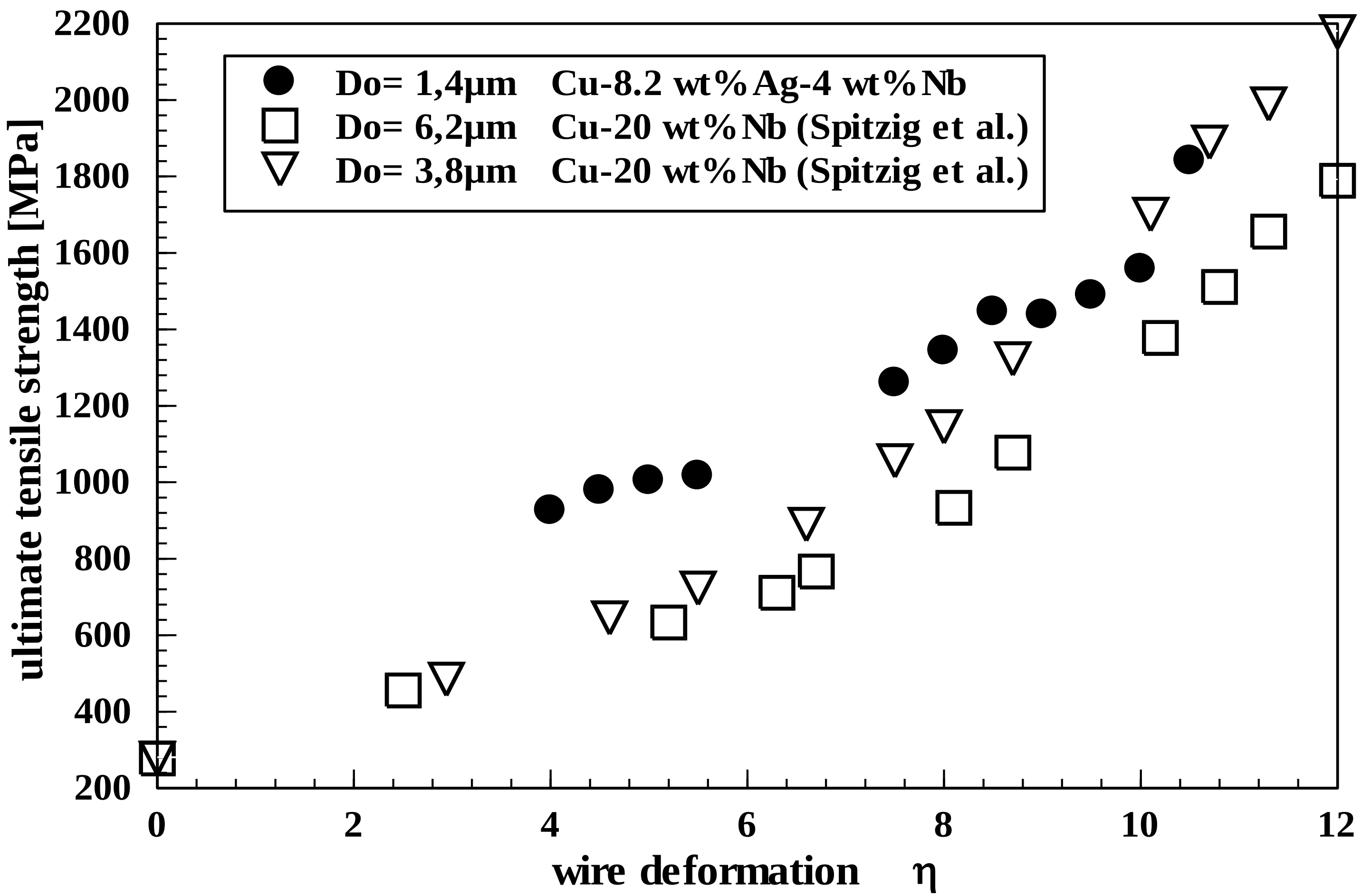
Fibres; Cu-5 at.% Ag-3 at.% Nb (Cu-8.2 wt% Ag-4 wt% Nb)



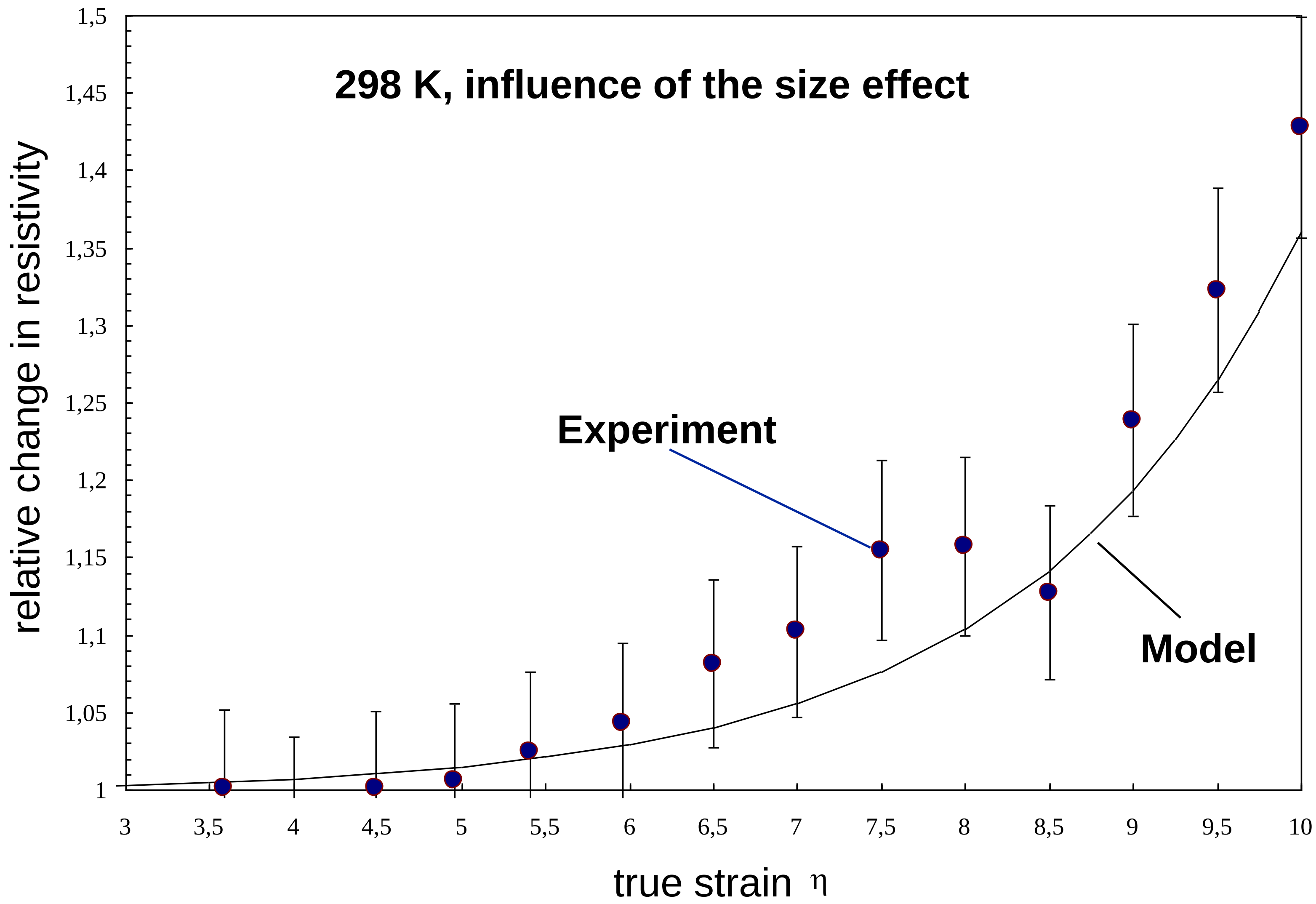
$\eta=7.5$ $\eta=8.6$ $\eta=10.0$



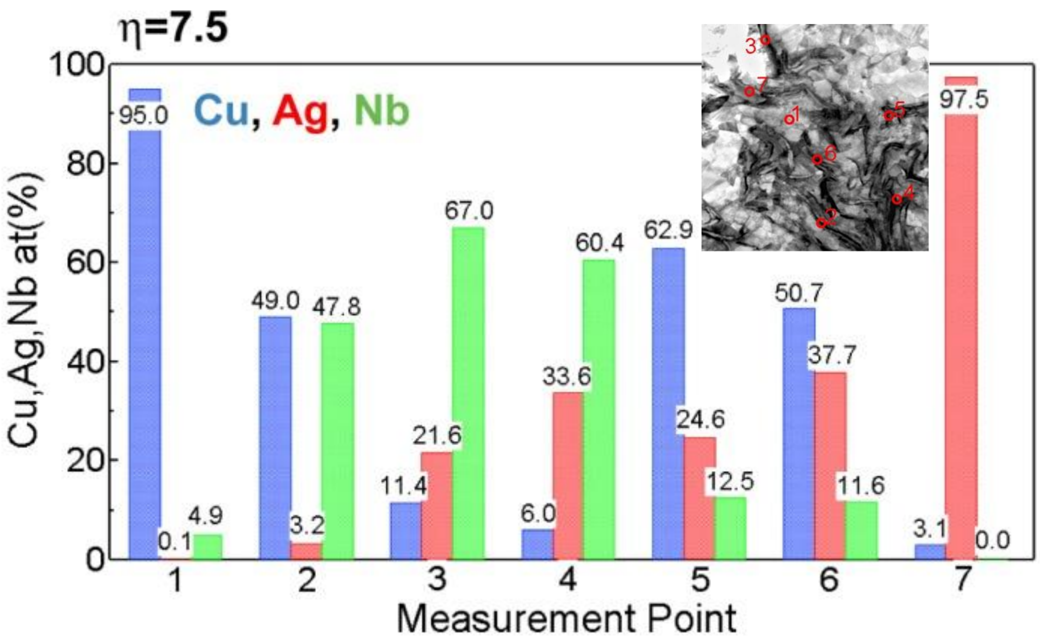
Binary vs. ternary strategy



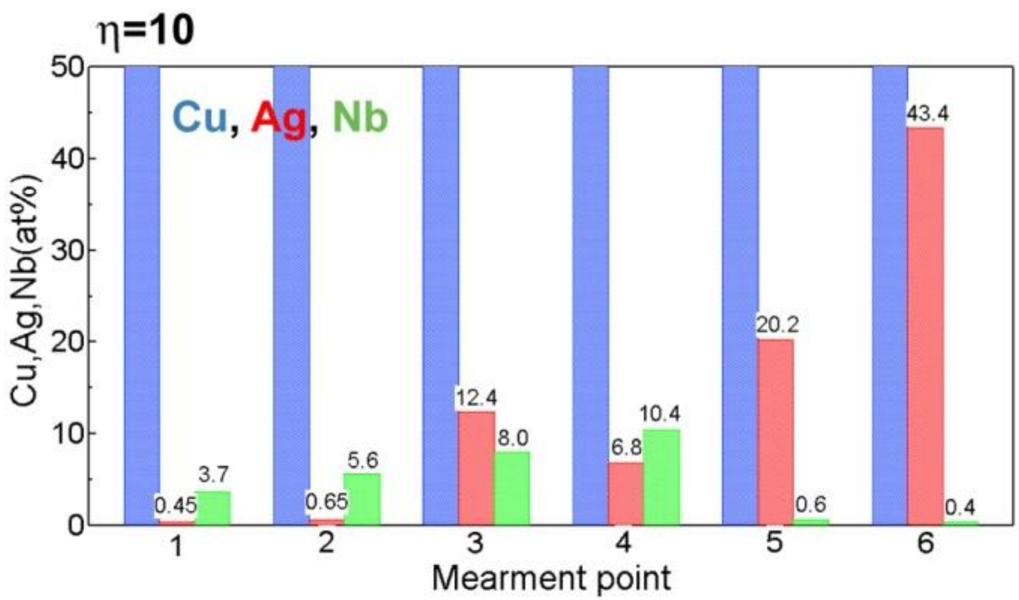
Res. conduct.; Cu-5 at.% Ag-3 at.% Nb (Cu-8.2 wt% Ag-4 wt% Nb)



Nano-beam energy dispersive x-ray spectroscopy (EDS)

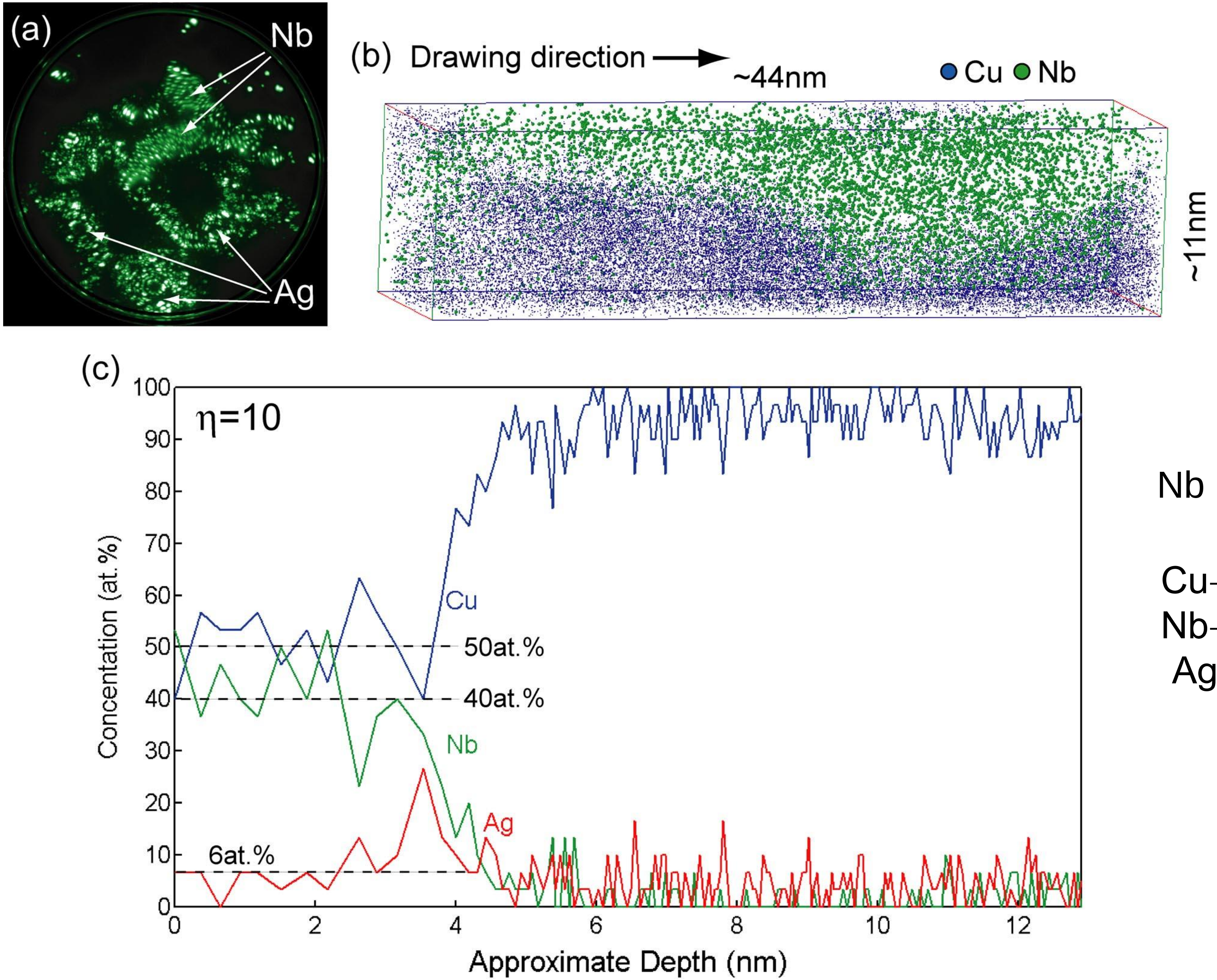


Point 1: Cu matrix
Point 2: Nb filament
Points 3-6: Nb and Ag with varying fractions, partly because of the convolution effect of EDS
Point 7: Ag fiber.



Dominance of Cu
Points 1 and 2: minor Nb contribution
Points 3-6: considerable Ag contribution
Strong co-existence of Cu and Ag within the same beam probes

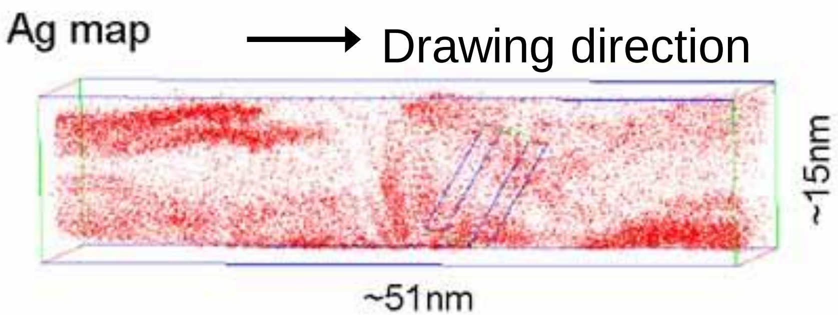
Nb fiber: η=10.0

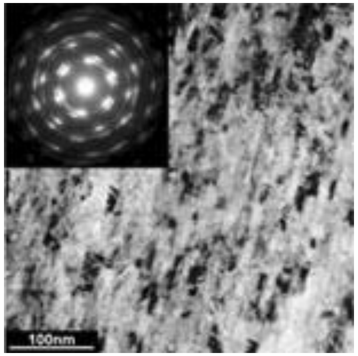


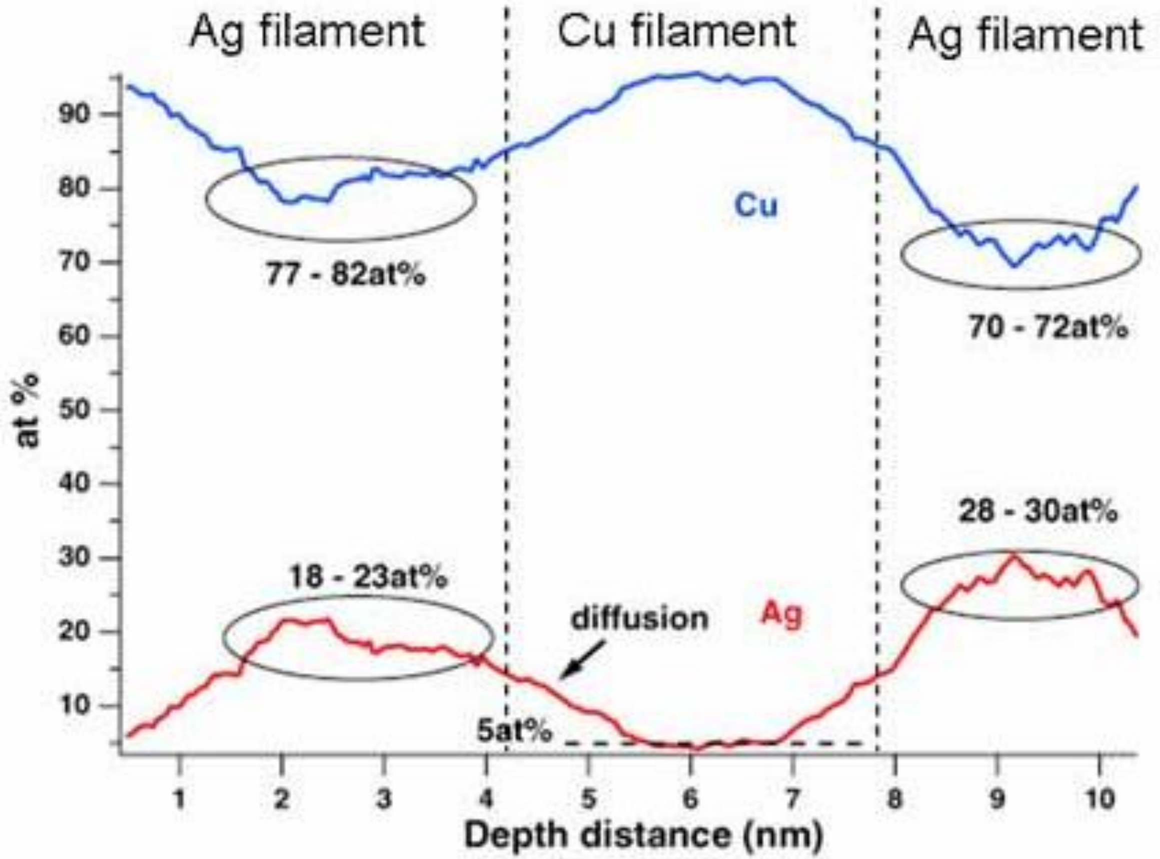
Nb phase

Cu→40~60at%
Nb→20~50at%
Ag→5~28at%

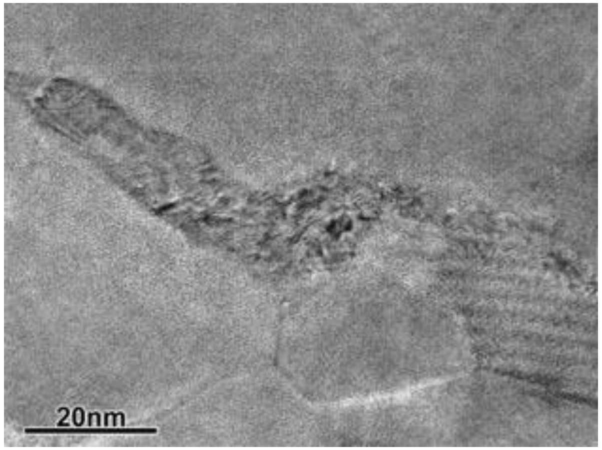
Ag fiber: η=10.0

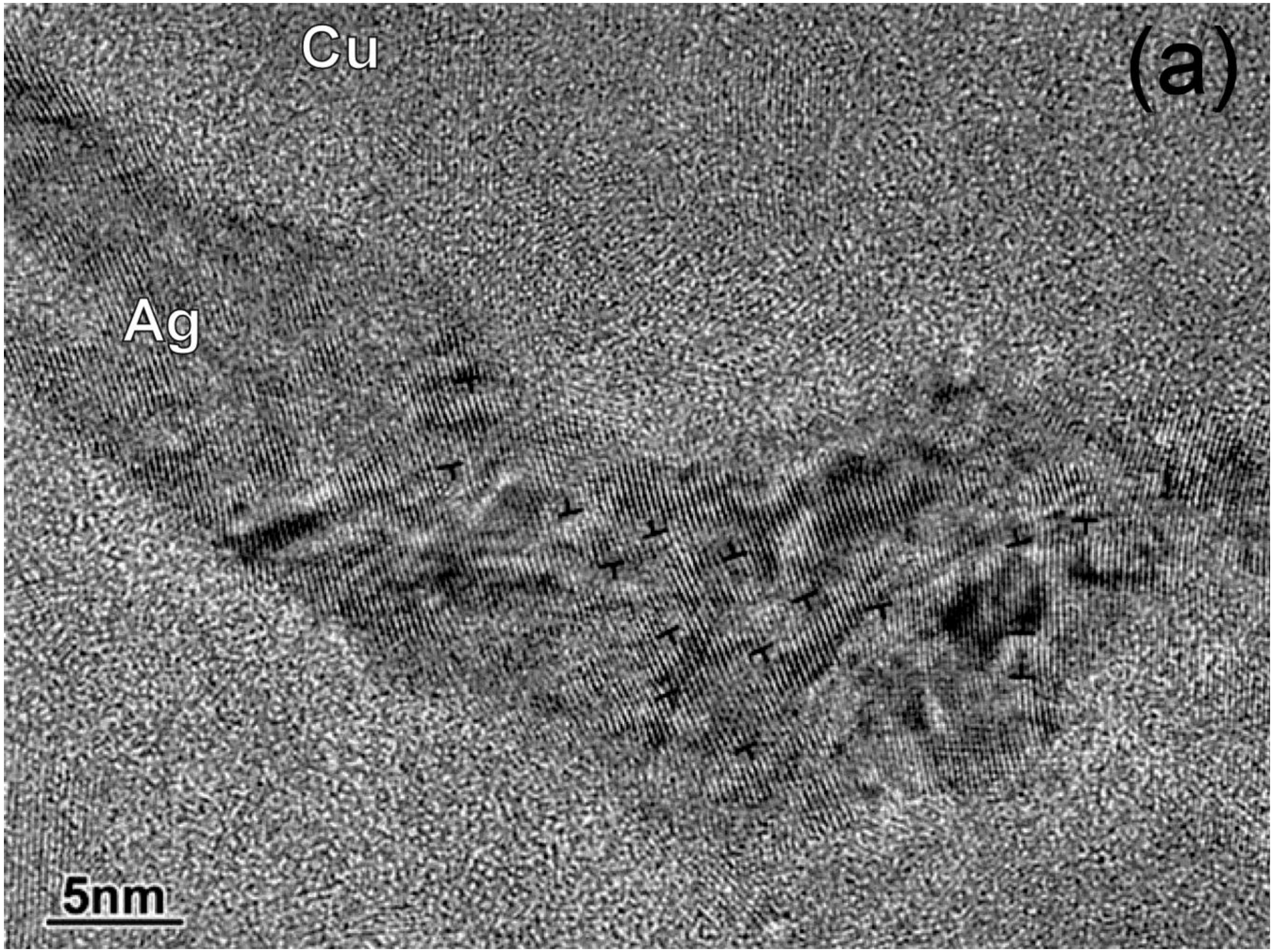






η=10.0 Ag phase

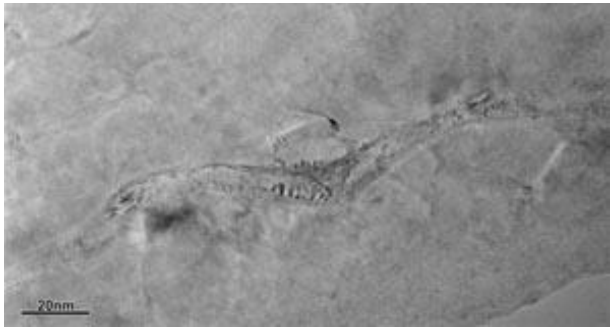


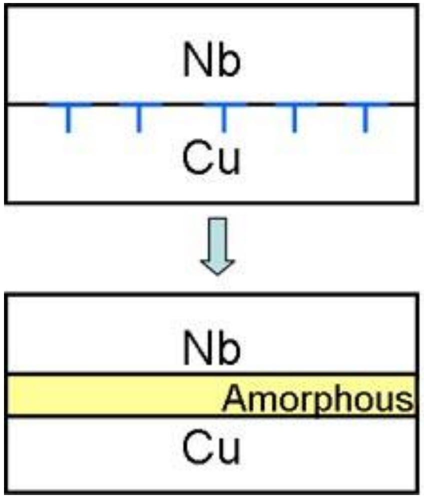


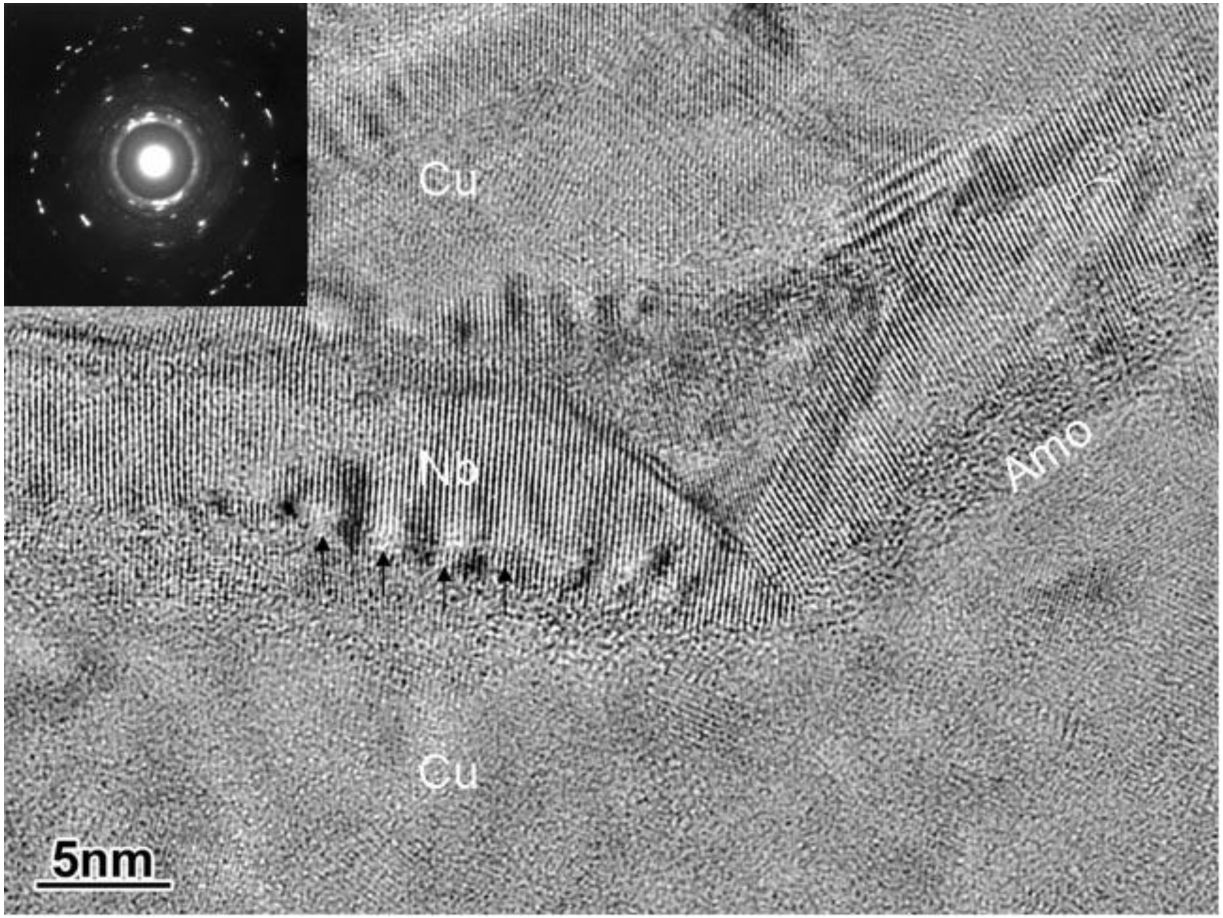
Dislocation density $4.0 \times 10^{16} m^{-2}$

Raabe, Ohsaki, Hono: Acta Mater. 57 (2009) 5254

Amorphization at Cu/Nb interface







D. Raabe, U. Hangen: Materials Letters 22 (1995) 155–161; D. Raabe, F. Heringhaus, U. Hangen, G. Gottstein: Zeitschrift für Metallkunde 86 (1995) 405–422; D. Raabe, U. Hangen: Journal of Materials Research 12 (1995) 3050–3061

see also: X.Sauvage: University of Rouen

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Discussion: mechanically-induced mixing

Classical difffusion
Cu-Nb and Cu-Ag: negligible solubility
No thermodynamic driving force for mixing
Interface thermodynamics and solubility
No negative enthalpy of mixing in case of crystalline phase
Also Gibbs–Thomson effect and internal stresses do not provide negative mixing enthalpy
Annealing: immediate de-mixing and spherodization

Plasticity-assisted diffusion
Deformation-induced increase in vacancy density
All phases in the alloy, i.e. Cu, Ag, and Nb plastically strained
An increased vacancy concentration should be present in all phases
If higher defect densities enhance diffusion, the mixing profiles should be symmetric
Atomic-scale interface roughening
Pipe diffusion
Segregation and diffusion to dislocation cores in neighbor phase

Dislocation shuffle

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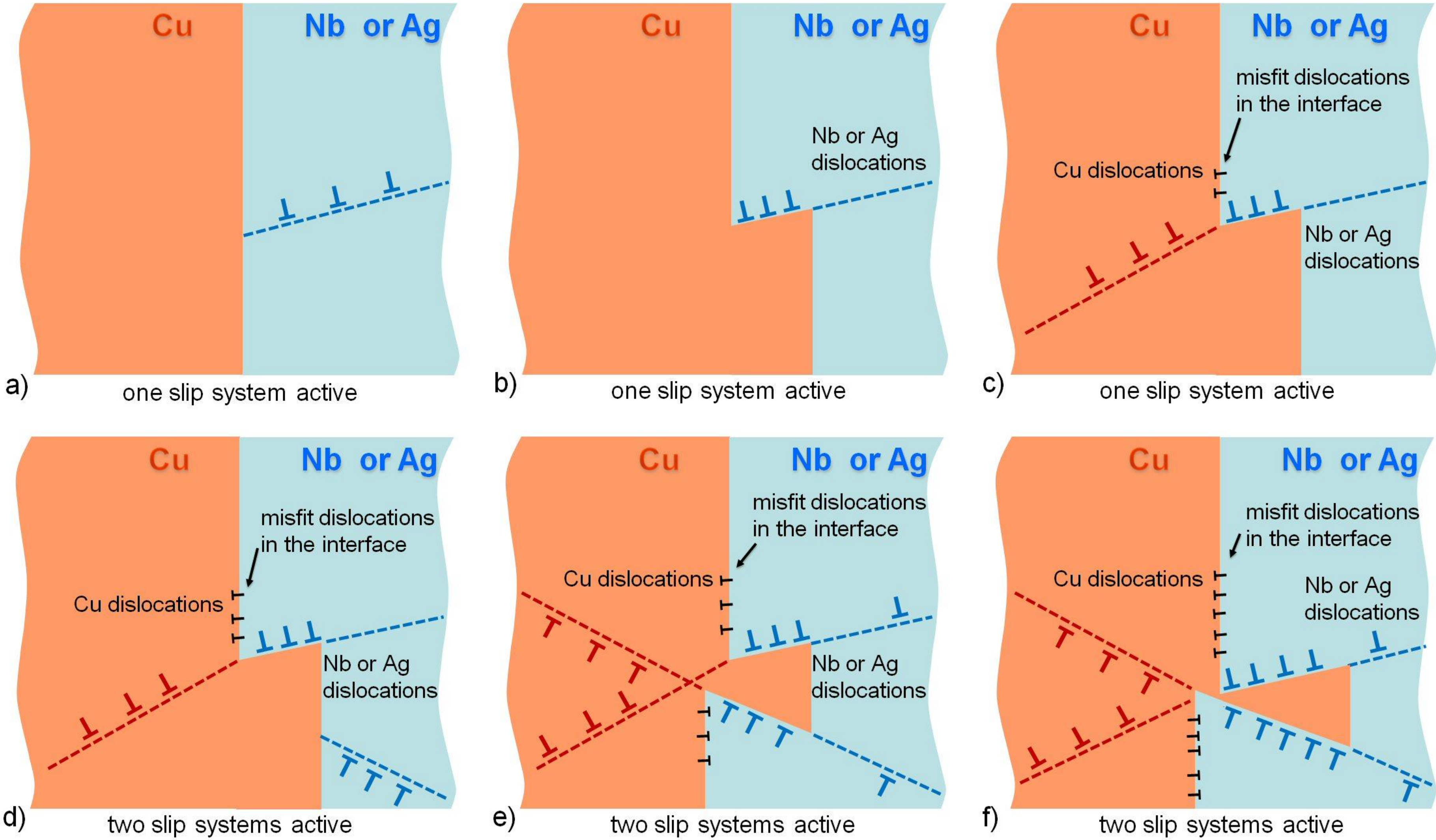
Discussion: mechanically-induced mixing



Discussion: mechanically-induced amorphization

Pure Cu, Ag, and Nb wires not amorphous during wire drawing

Relationship between mechanical alloying, enthalpy of mixing of the newly formed compounds, and subsequent amorphization.

Abutting phase of an amorphous Cu region shows high dislocation densities

Cu matrix becomes amorphous only when mechanically alloyed.

Occurs in Cu-Nb, Cu-Nb-Ag, and Cu-Zr: In all cases at least one pair of the constituent elements reveal a negative enthalpy of mixing.

Gibbs free energy - concentration diagram reveals amorphous Cu-Nb phase between 35 at.% and 80 at.% relative to the BCC and FCC solid solutions that could be formed by forced mixing. Our measurements fall in this regime. The atomic radius mismatch is 12.1% for Cu-Nb, 13.1% for Cu-Ag, and even 24.4% for Cu-Zr.

Total free energy change due to dislocation energy not enough

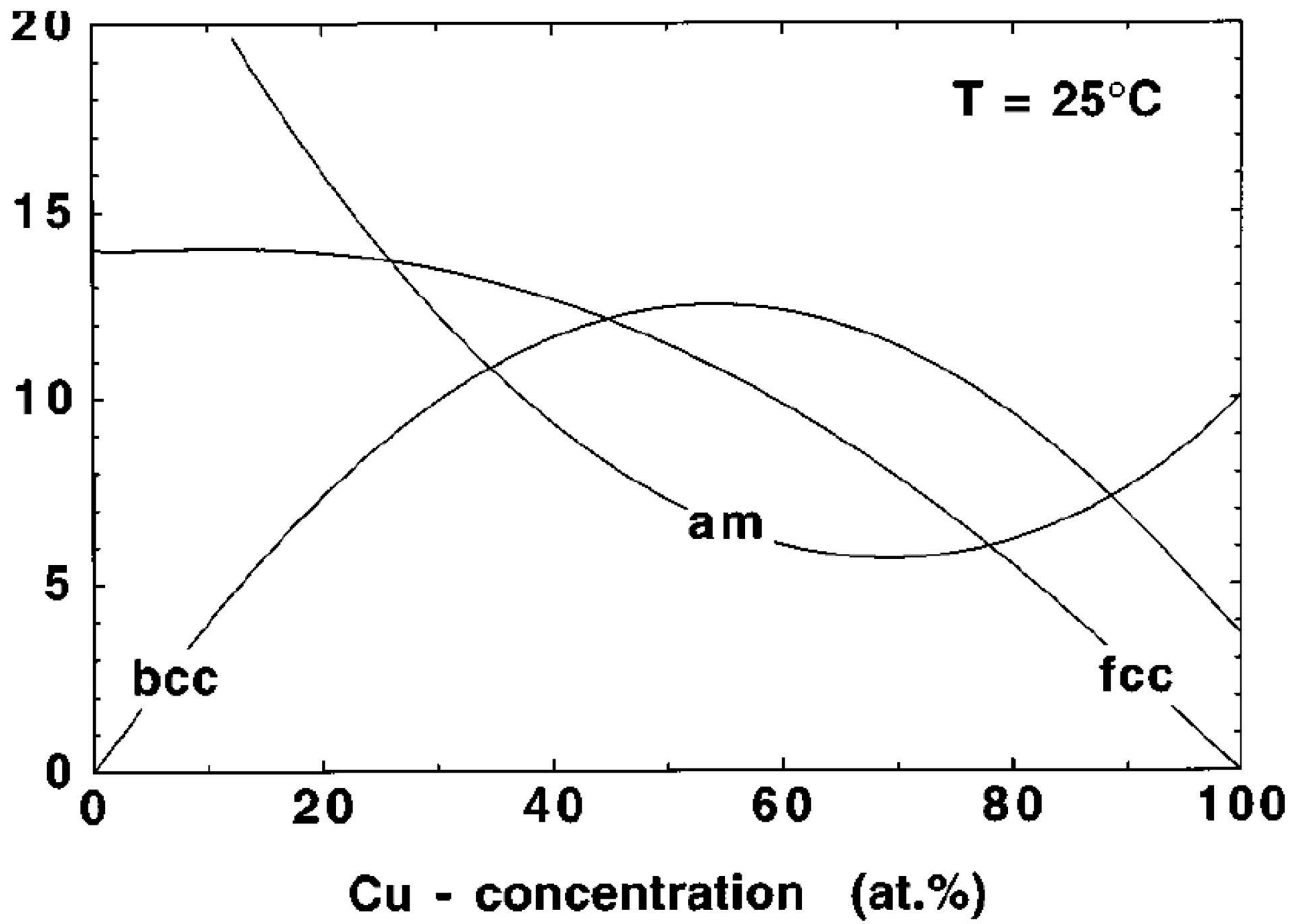
Amorphization in a two step mechanism:

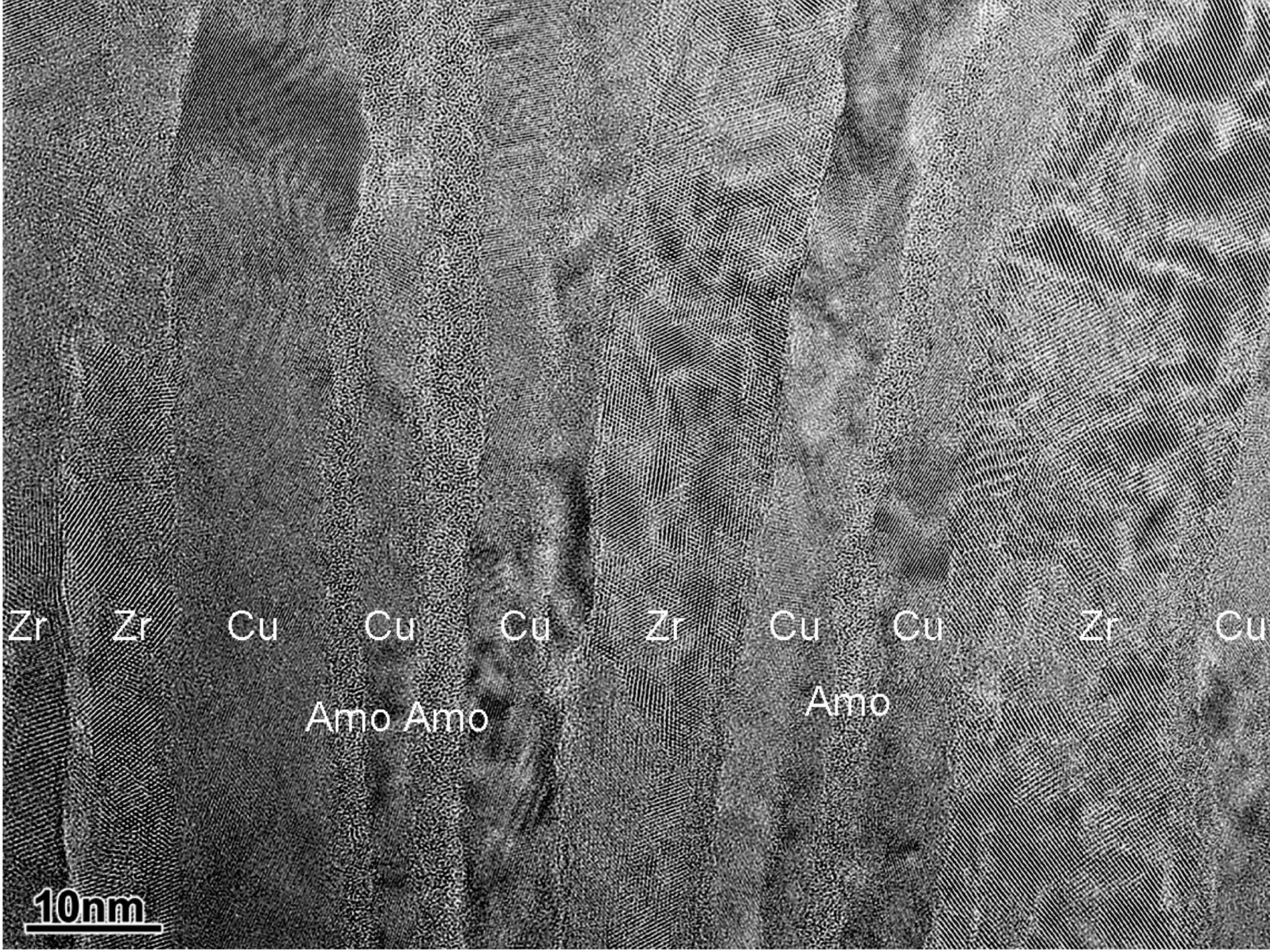
Dislocation-shuffling /trans-phase plastic deformation and mixing

Amorphization in regions with both, heavy mixing and high dislocation densities

Likely in systems which fulfill at least some of the classical glass forming rules.

Discussion: mechanically-induced mixing and amorphization




Zr
Zr
Cu
Cu
Cu
Zr
Cu
Cu
Zr
Cu
Amo
Amo
Amo
10nm

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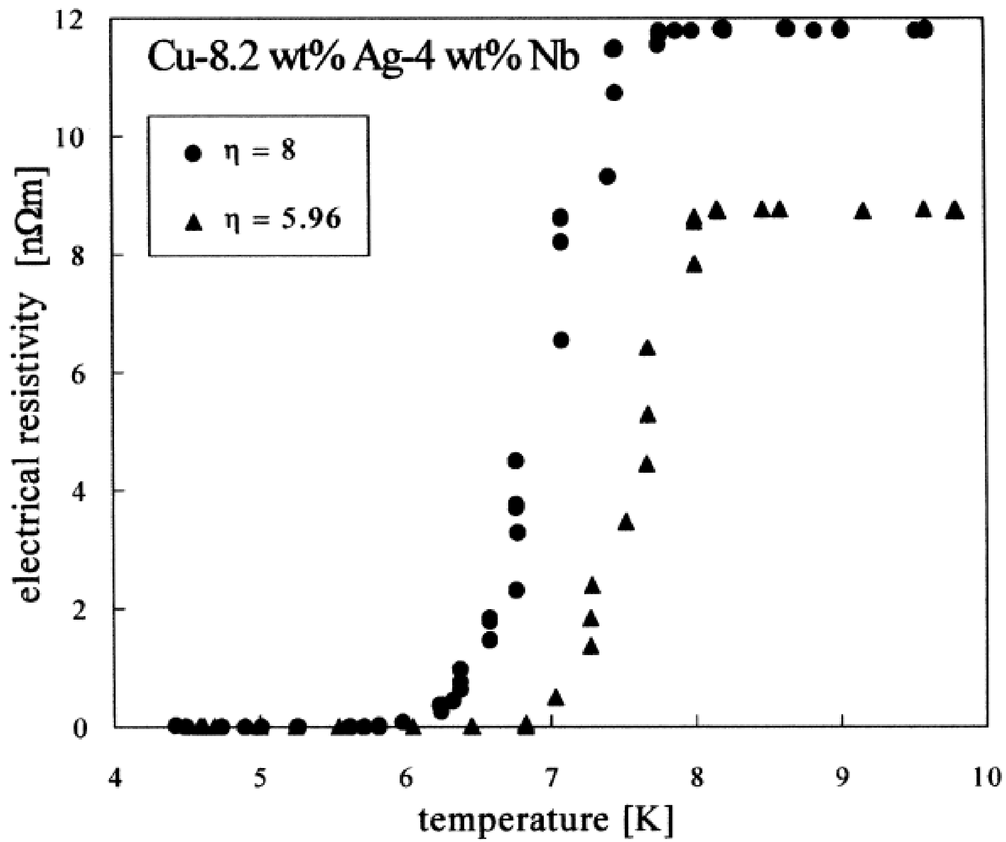
Mechanism of mechanical alloying and amorphization

Superconductivity and proximity effects dependent on local mechanical mixing



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(Cu-8.2wt%Ag-4wt%Nb)