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

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- 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; heterophase dislocation transmission; amorphization; conductivity)
- Melt, cast, wire; SEM, TEM, APT
Why Cu-5 at.% Ag-3 at.% Nb

Nb
Ag/Cu
Cu

binary

ternary

nm-spacing: high strength low scattering
Motivation and Methods

Results

Discussion

Outlook and open questions
Fibres; Cu-5 at.% Ag-3 at.% Nb (Cu-8.2 wt% Ag-4 wt% Nb)
Binary vs. ternary strategy

298 K, influence of the size effect

Model

Experiment

Res. conduct.; Cu-5 at.% Ag-3 at.% Nb (Cu-8.2 wt% Ag-4 wt% Nb)
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: $\eta=10.0$

(a) [Image of Nb and Ag]

(b) Drawing direction $\sim 44\text{nm}$

Cu $\rightarrow$ 40$\sim$60at%

Nb $\rightarrow$ 20$\sim$50at%

Ag $\rightarrow$ 5$\sim$28at%

(c) [Graph showing concentration vs. approximate depth]

$\eta=10$

Cu

$6\text{at.}\%$

$40\text{at.}\%$

$50\text{at.}\%$

Ag

$6\text{at.}\%$

Approximate Depth (nm)
Ag fiber: $\eta = 10.0$
\( \eta = 10.0 \) Ag phase

Dislocation density \( 4.0 \times 10^{16} \text{m}^{-2} \)

Raabe, Ohsaki, Hono: Acta Mater. 57 (2009) 5254
Amorphization at Cu/Nb interface

\( \eta = 10.0 \) Nb phase


see also: X. Sauvage: University of Rouen

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Discussion: mechanically-induced mixing

Classical diffusion
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
Discussion: mechanically-induced mixing

- **a)** one slip system active
- **b)** one slip system active
- **c)** one slip system active
- **d)** two slip systems active
- **e)** two slip systems active
- **f)** two slip systems active
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
Motivation and Methods

Results

Discussion

Outlook and open questions
Mechanism of mechanical alloying and amorphization

Superconductivity and proximity effects dependent on local mechanical mixing

Outlook and open questions

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