Effect of Strain Rate on the Fabrication of SRF Cavities and on the Properties of Niobium and Copper

EASISchool 3 Student Workshop – 08/10/2020

Jean-François Croteau jean-francois.croteau@icube-research.com

Collaborators

I-Cube Research: Elisa Cantergiani
CERN: Said Atieh, Ana Teresa Perez Fontenla, Elisa Garcia-Tabares Valdivieso
MSU: Eureka Pai Kulyadi, Di Kang, Thomas Bieler, Philip Eisenlohr
ASU: Chaitanya Kale, Kiran Solanki
Imperial College: Derek Siu, Paul Hooper, Daniel Balint
BAM: Leonardo Agudo, Anna Manzoni
JRC: Marco Peroni
ENSTA Bretagne: Nicolas Jacques

EASITrain – European Advanced Superconductivity Innovation and Training. This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) has received funding from the European Union's H2020 Framework Programme under Grant Agreement no. 764879

Side note before we start

- Since this is a student workshop, some slides present practical characterization techniques or some theory

Look out for this tag!

Outline

- SRF cavity fabrication
- Sheet forming with electro-hydraulic forming
- Characterization of copper and niobium
  - Properties of electron beam welded specimens
  - Properties of niobium single crystals
- Conclusions and future work

SRF Cavities and Electro-Hydraulic Forming (EHF)

Outline

- SRF cavity fabrication
- Sheet forming with electro-hydraulic forming
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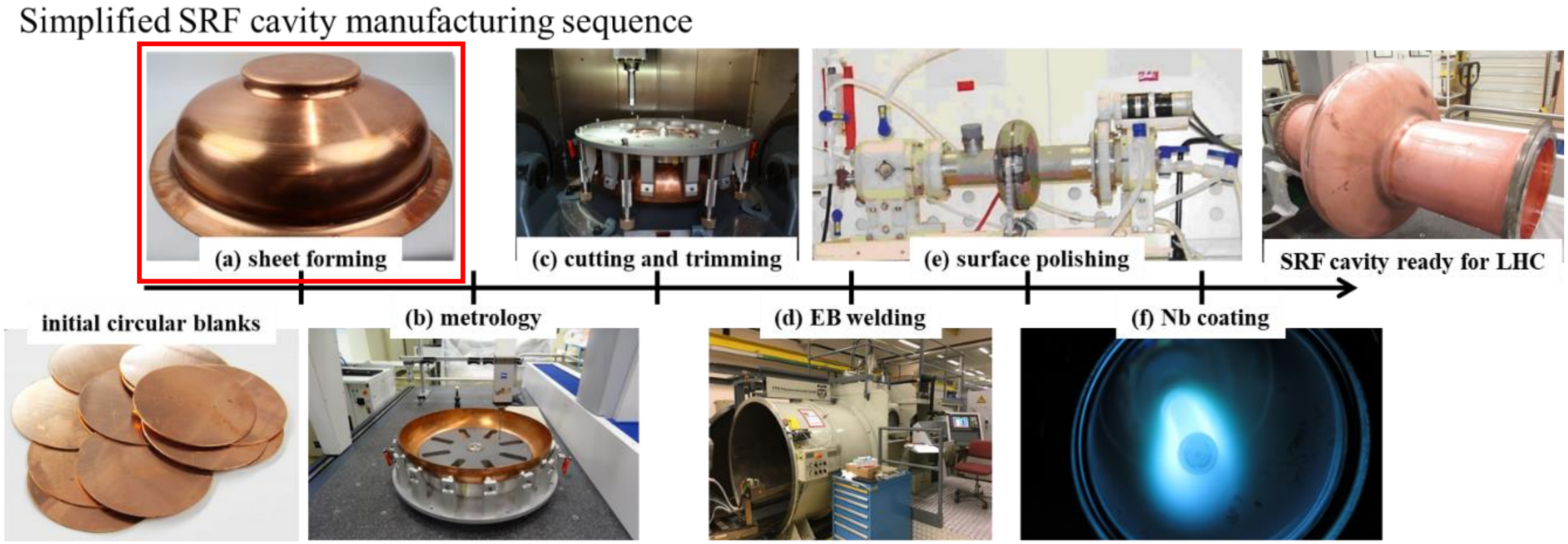
SRF Cavities Forming Sequence

- Only the sheet forming is done at I-Cube Research
- Other steps are done a CERN

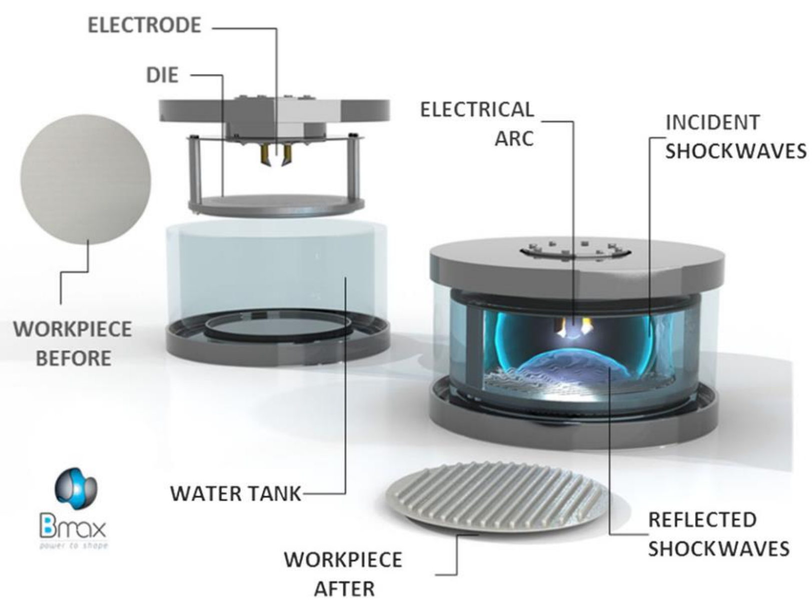
See talk of Daniele Sertore (29/09/2020) for more details about SRF cavity manufacturing

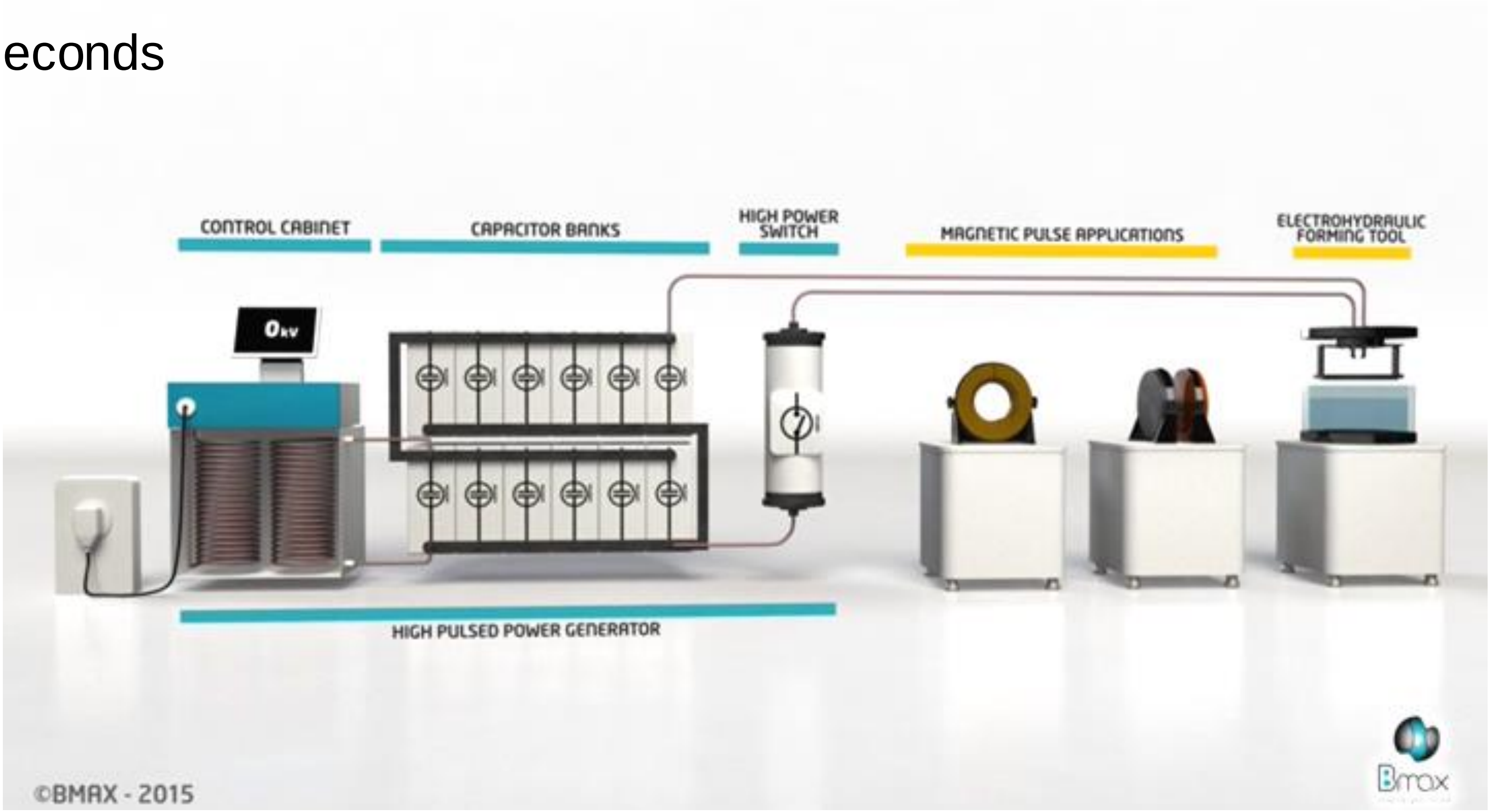
- Material characterization is essential for forming with electro-hydraulic forming



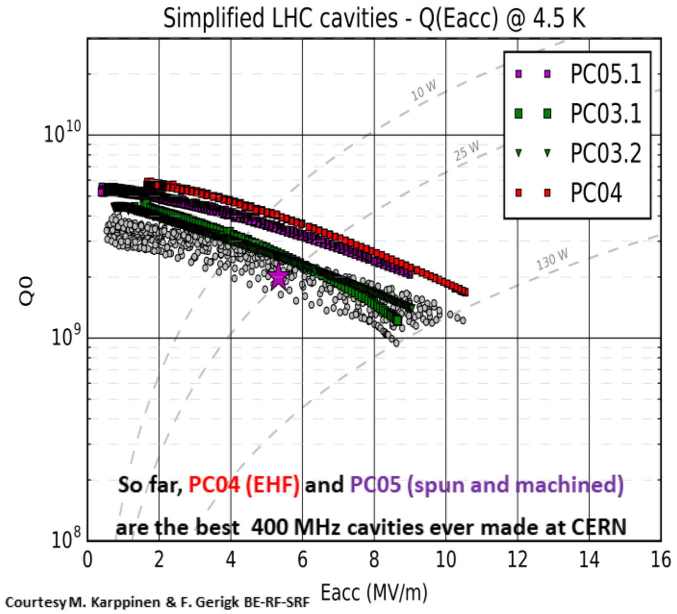
Electro-Hydraulic Forming (EHF)

- Electric arc from a high voltage discharge between electrodes
- High speed deformation from shockwave in water impacting on blank
- No contact between metallic die and inner surface of part (RF surface)
- Forming steps of 100s of microseconds





EHF Applied to SRF Cavities



Performances measured at CERN

- Higher performances than a cavity manufactured with spinning and machining [2]

Advantages [1]

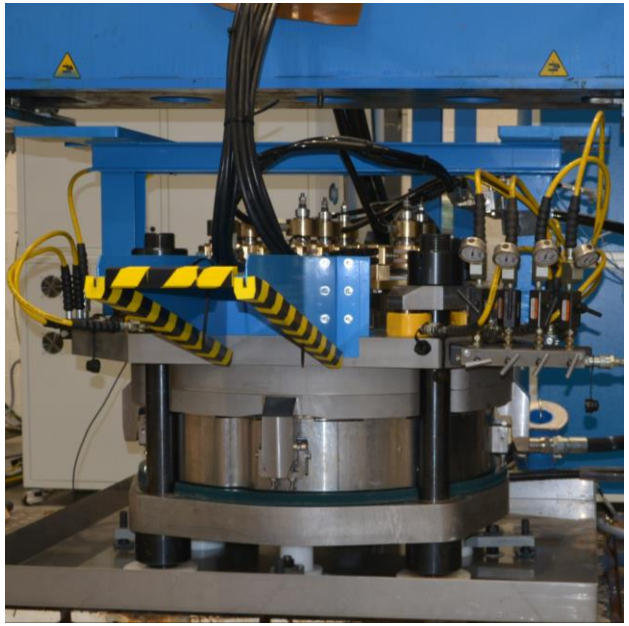
- High shape accuracy
- High reproducibility
- Thinner affected later
- No intermediate heat treatments required

Previous projects

- 400 MHz OFE copper half-cells formed for the spare parts of the LHC
- 700 MHz niobium half-cell formed for the FCC and for material characterization

Ongoing projects

- 800 MHz niobium half-cells for the FCC and a full characterization of the RF performances

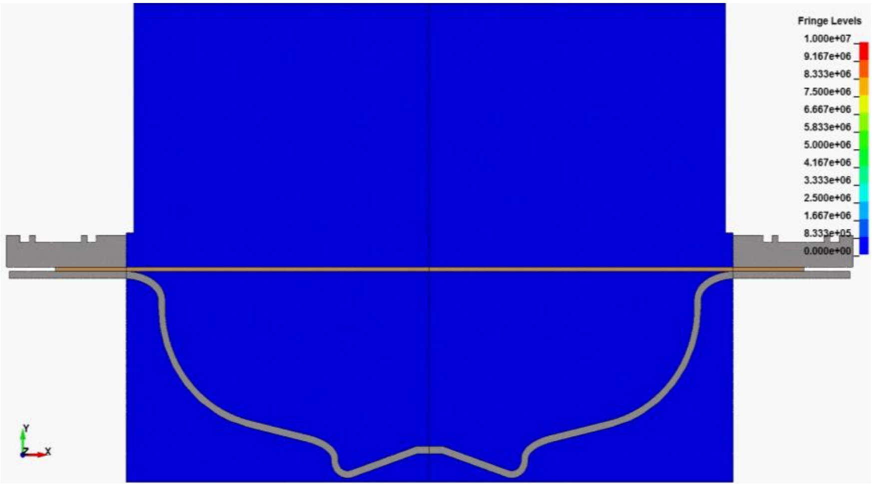


EHF production system used to form half-cells

[1] E. Cantergiani *et al.*, "Niobium superconducting rf cavity fabrication by electrohydraulic forming," *Physical Review Accelerators and Beams*, vol. 19, no. 11, Nov. 2016, doi: 10.1103/PhysRevAccelBeams.19.114703.

[2] S. Atieh, "Novel Technologies applied to SRF (cavity) fabrication," presented at the TTC 2020, Geneva, Switzerland, Feb. 05, 2020, [Online]. Available: https://indico.cern.ch/event/817780/contributions/3716472/

Forming Sequence with EHF



LS-Dyna Multiphysics simulation

Die-splitter setup for EHF

400 MHz half-cells for the LHC

700 MHz half-cells for the FCC

1. Simulation of the forming process

Dependent on:
- Mechanical properties of blank
- Cavity frequency
- Forming parameters

→

2. Machining of compensated die

Compensated die to account for sheet thinning and springback in different regions, based on the finite element simulations

→

3. Sheet forming

Rapid and reliable forming in a few shots of hundreds of microseconds

Mechanical Properties of Niobium and OFE Copper

Outline

- SRF cavity fabrication
- Sheet forming with electro-hydraulic forming
- Characterization of copper and niobium
  - Properties of electron beam welded specimens
  - Properties of niobium single crystals
- Conclusions and future work

Research Objectives for the EASITrain Project

Role of I-Cube Research

- 5 projects were initiated to characterize the mechanical properties of SRF cavity substrates

1. 800 MHz niobium half-cells
Forming of 800 MHz Nb half-cells with electro-hydraulic forming (EHF) at Bmax

2. Forming limit diagrams (FLD) of Nb and OFE-Cu
Determination of the quasi-static forming limit diagram of annealed OFE-Cu and polycrystalline high RRR Nb

LABORATOIRE D'ÉTUDE DES MICROSTRUCTURES ET DE MÉCANIQUE DES MATÉRIAUX

3. Characterization of OFE-Cu at high strain rates
Determination of material constitutive laws to implement in a finite element code for prediction of EHF

Institut de Recherche Dupuy de Lôme — Imperial College London

Today

4. Characterization of electron beam welded sheets
Study on the mechanical properties of EB welded OFE-Cu and Nb specimens at low and high strain-rates in tension and compression

JRC European Commission — Institut de Recherche Dupuy de Lôme

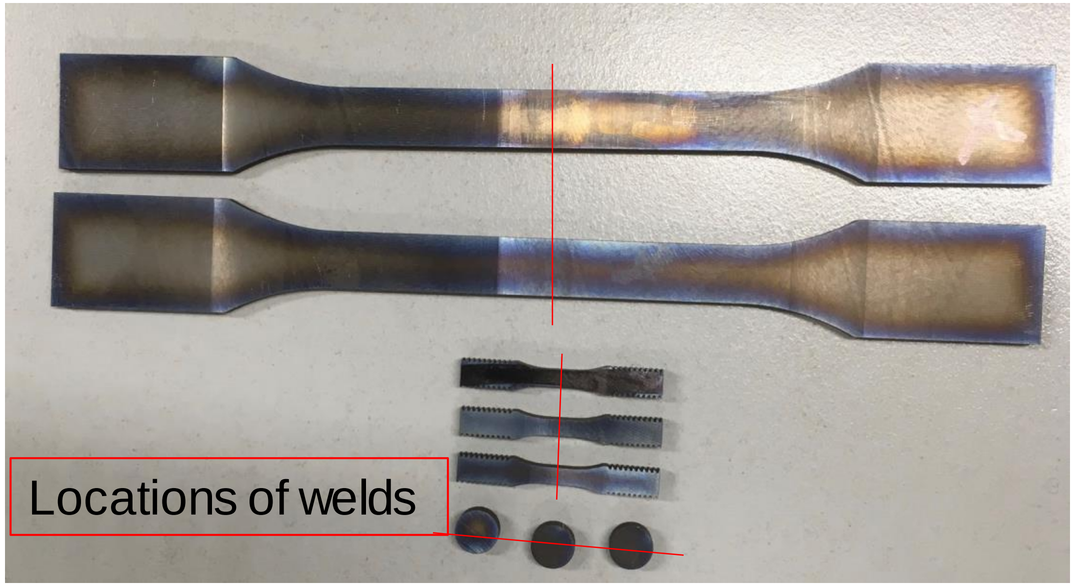
5. Characterization of niobium single crystals
First study of the mechanical properties of Nb single crystals at low and high strain rates in tension and compression

Michigan State University — Arizona State University — Imperial College London — Institut de Recherche Dupuy de Lôme

Properties of Electron Beam Welds at High Speed

- Why studying electron beam welded sheets?

1. Manufacturing of tubes with a bent and welded sheet for seamless cavities (talk V. Garcia 08/10)
2. Forming of complex welded components (e.g. crab cavities)



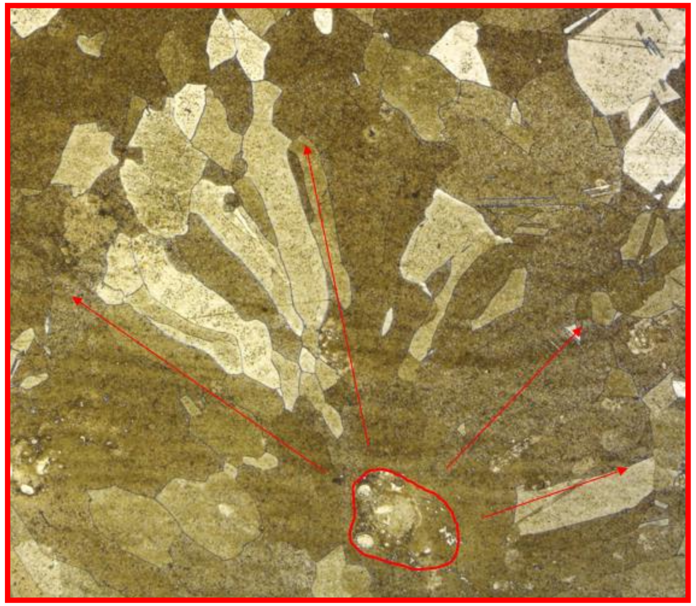
Welded tensile and compression niobium specimens

Electron beam welding machine at CERN

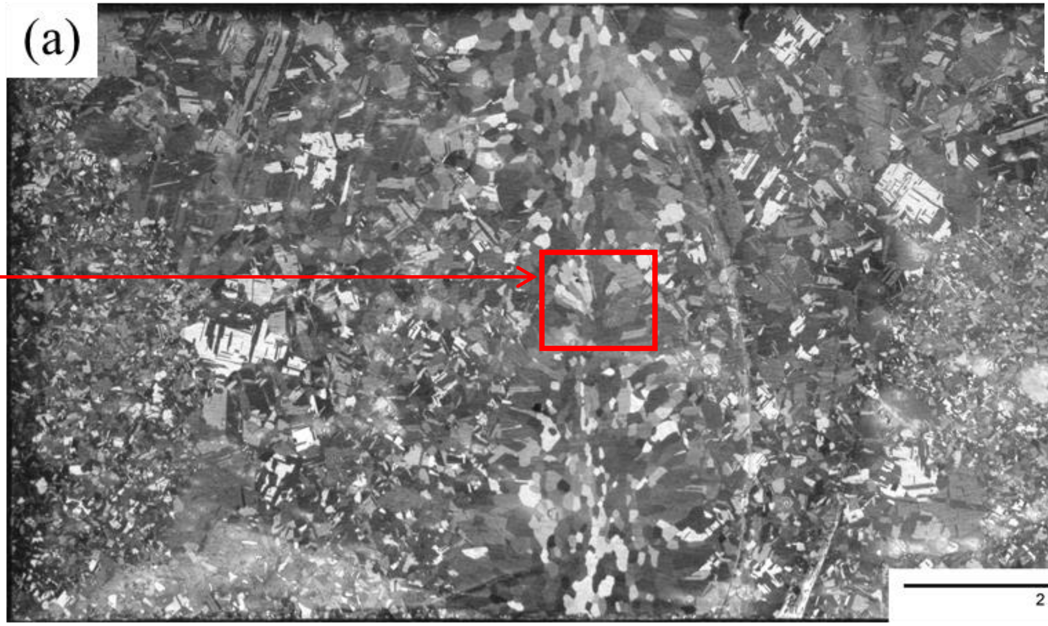
Properties of Electron Beam Welds at High Speed

- Characterization of electron beam (EB) welded OFE copper and niobium sheets at strain rates between 10^{-3} (0.01 mm/s) and 1,600 s^{-1} (8000 mm/s)

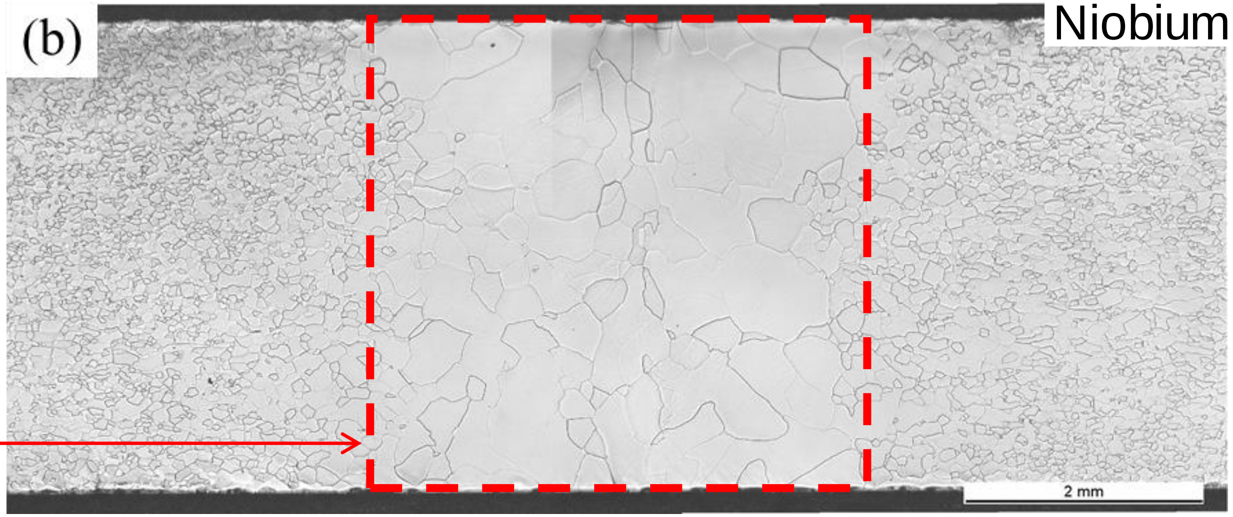
Fusion zone
Small grains with radial growth



Grain nucleation at pore



Copper

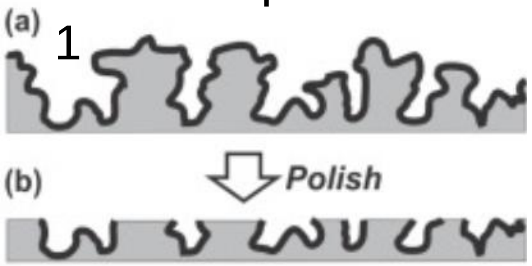


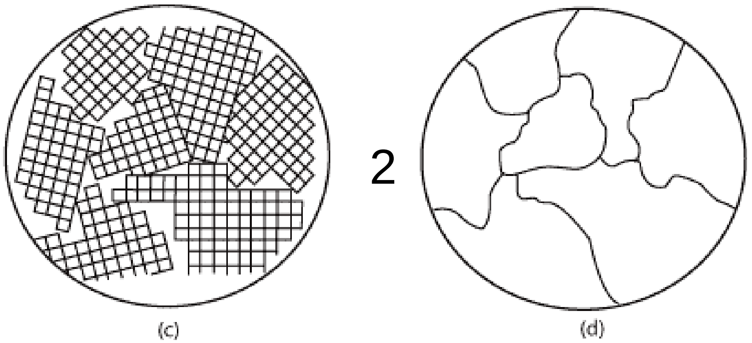
Niobium

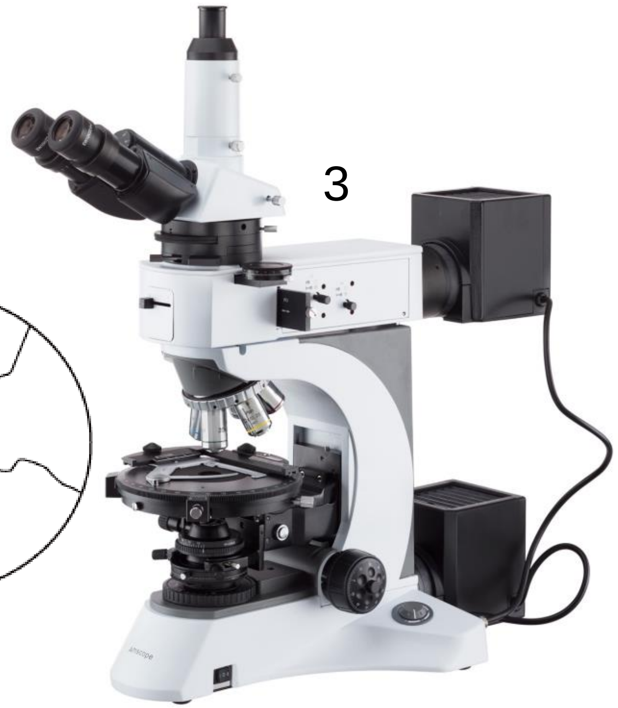
Fusion and heat affected zones
Large grains (up to 1.2 mm)

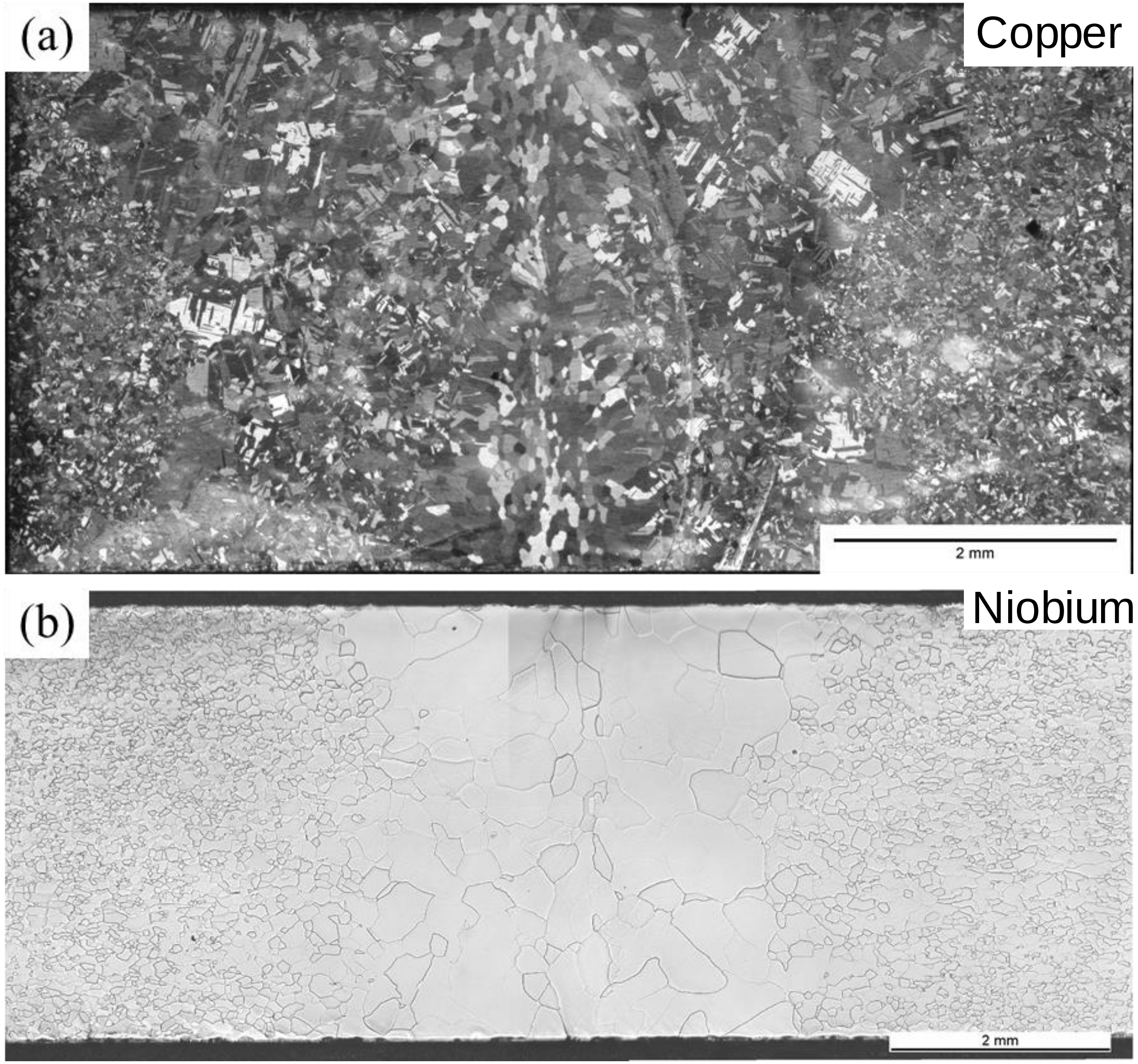
Properties of Electron Beam Welds at High Speed

- How to obtain these results?
  1. Mechanical polishing (mirror finish) [1]
  2. Chemical etching (reveals grain boundaries) [2]
  3. Optical microscope [3]







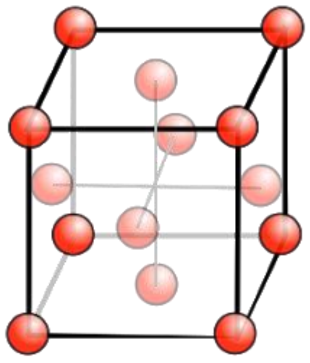


[1] https://doi.org/10.1016/j.sbsr.2016.05.006
[2] https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/solidification.html
[3] https://www.amscope.com/50x-1000x-advanced-upright-polarized-light-microscope.html

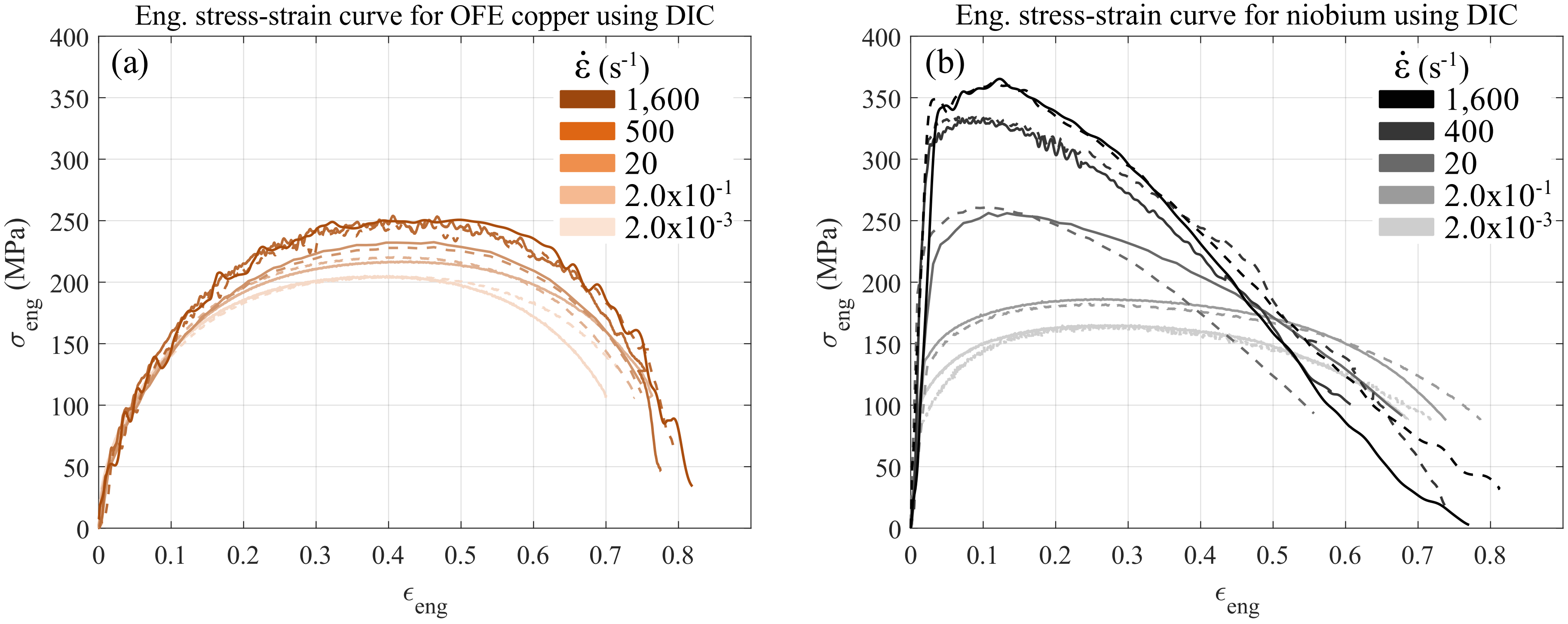
Properties of Electron Beam Welds at High Speed

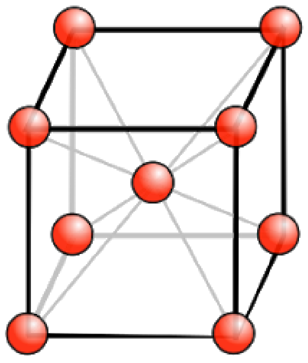
Learning

- Low strain rate sensitivity for OFE copper (similar yield stress and increase in strain hardening rate)
- High strain rate sensitivity for niobium (increase in yield stress and from hardening to softening)



FCC



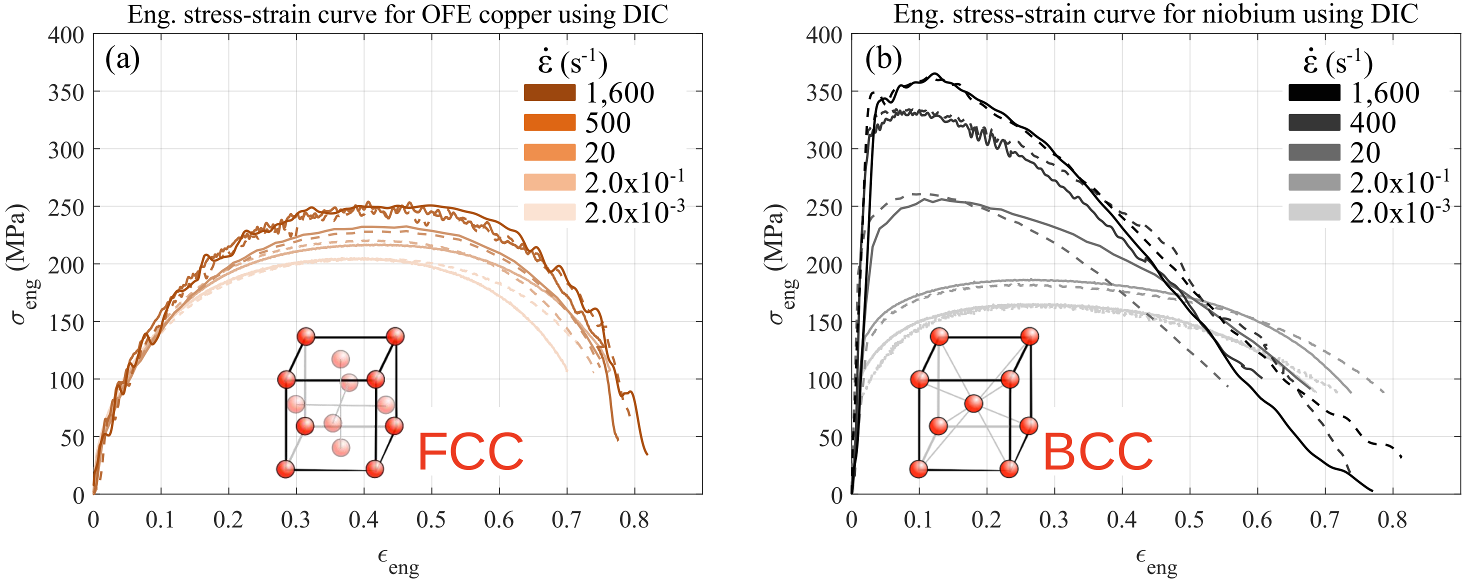


BCC

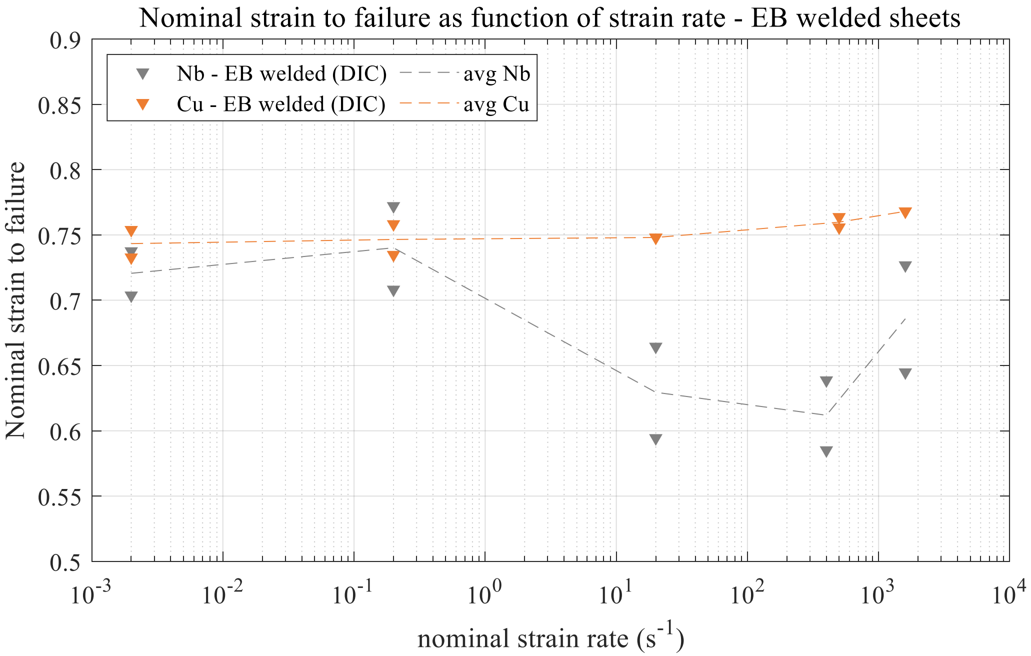
Tensile mechanical properties of OFE-Cu and Nb

Properties of Electron Beam Welds at High Speed

- Similar yield stress and ultimate tensile strength for welded and unwelded specimens
- Reduction of ductility for Nb at strain rates greater than 2.0×10^{-1} s^{-1} (minimum at 500 s^{-1})
- Large grains in fusion zone for Nb (~1 mm) → anisotropic necking and failure



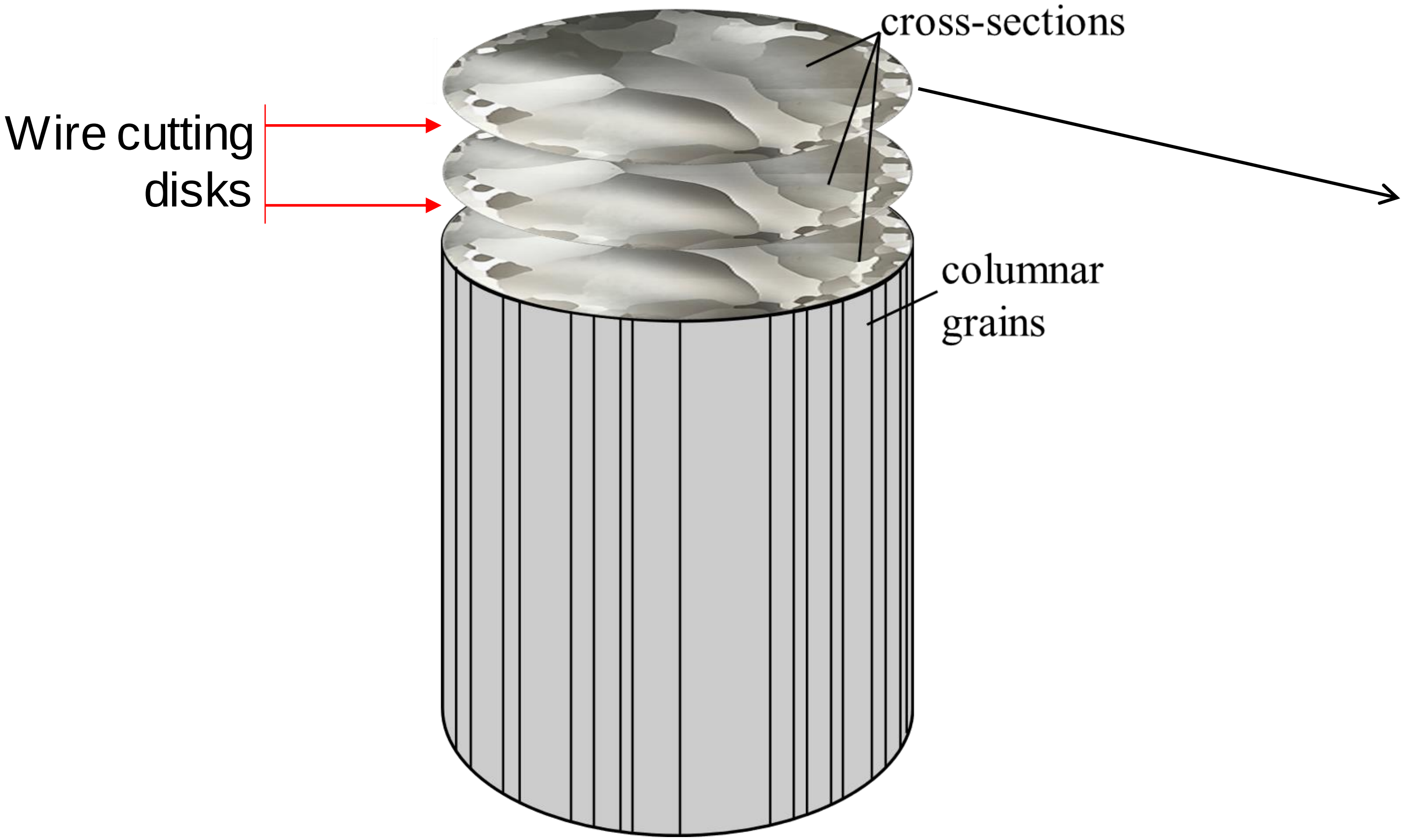
Tensile mechanical properties of OFE-Cu and Nb



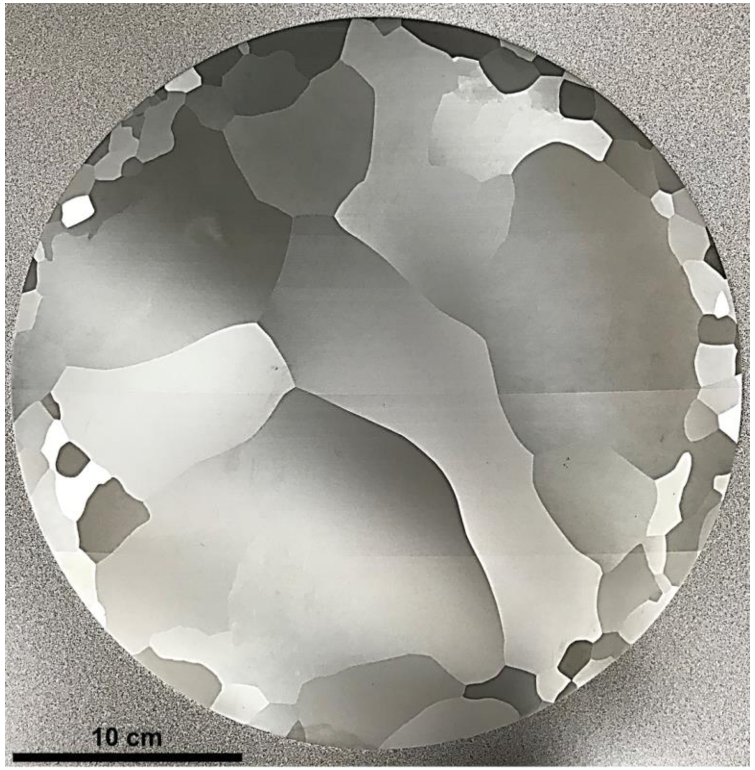
Strain rate sensitivity of ductility

Mechanical Properties of Niobium Single Crystals

- Large grain niobium disk of 320 mm in diameter
- Single crystal specimens extracted from the grains
- High purity RRR > 300



Niobium ingot with large columnar grains



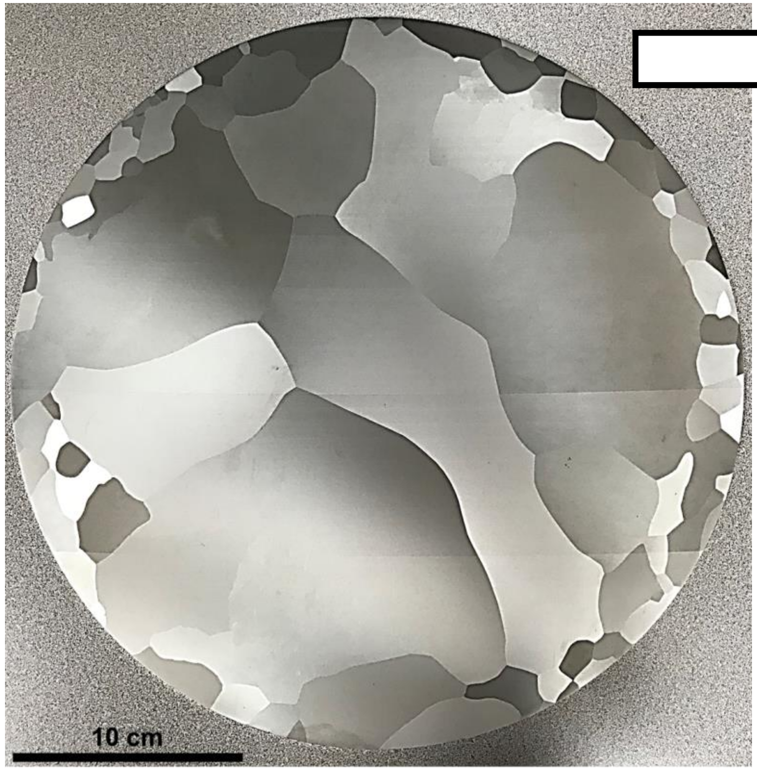
Original disk with large grains

Mechanical Properties of Niobium Single Crystals

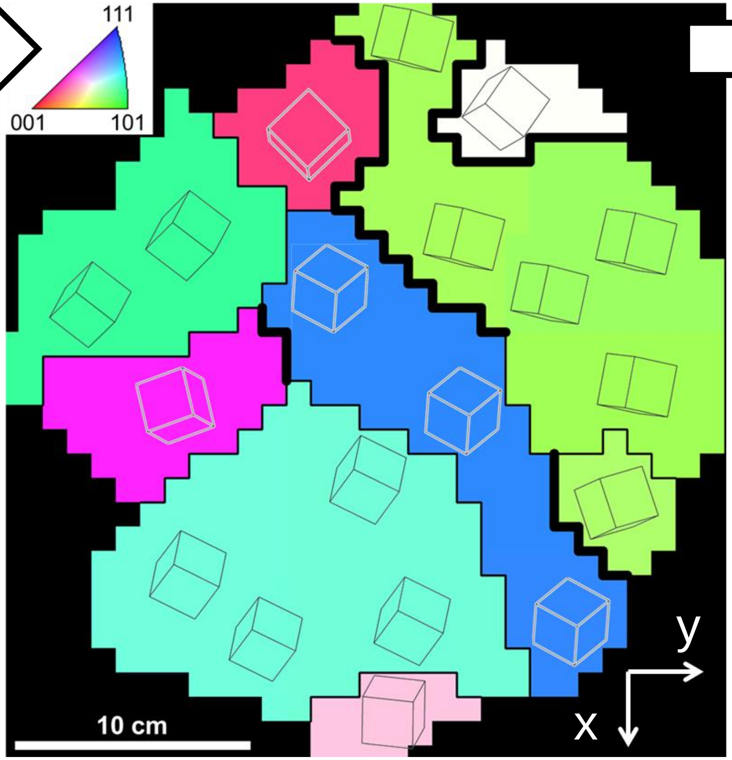
- Large grain niobium disk of 320 mm in diameter
- Single crystal specimens extracted from the grains
- High purity RRR > 300

Crystal orientation measurement

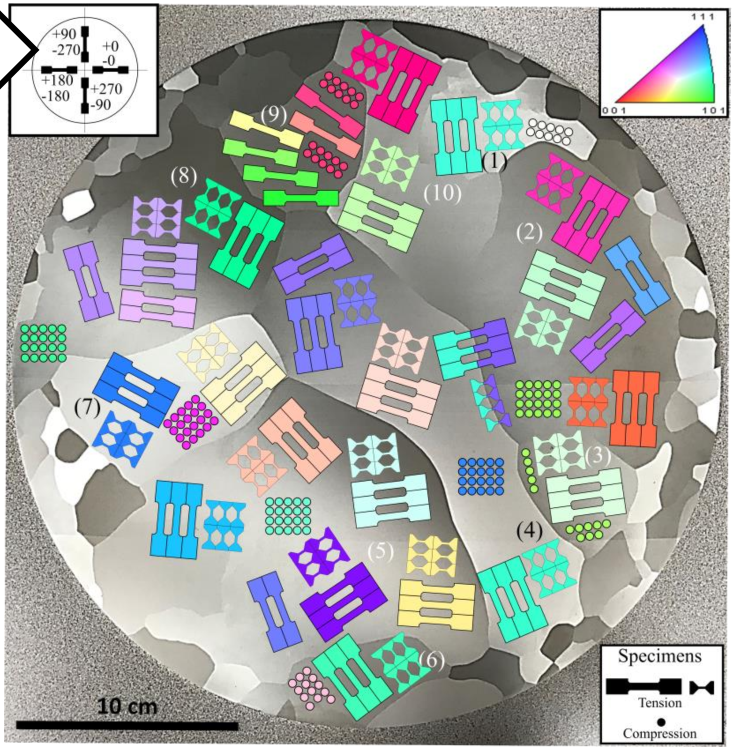
Tensile specimen orientation selection



Original disk with large grains



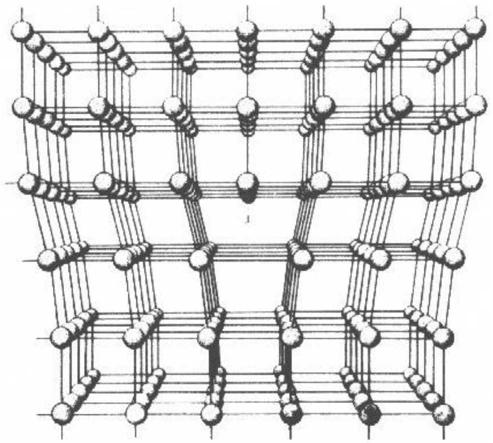
Measured grain orientations



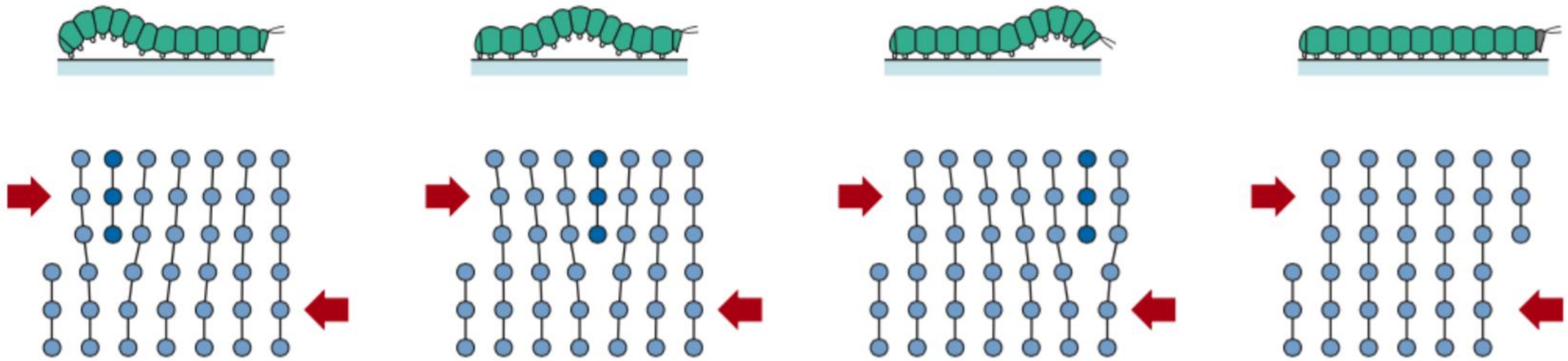
Layout of specimens on large grain disk

Dislocations and Plasticity

- What are dislocations?
    - Linear defects in a crystal (edge, screw or mixed type)
- Dislocations nucleation and motion are responsible for plastic deformation and their interaction explains hardening (plasticity)
- Without dislocations (defects in the lattice), the load to deform the crystals would be too high
    - Break all bounds to move by one atomic position

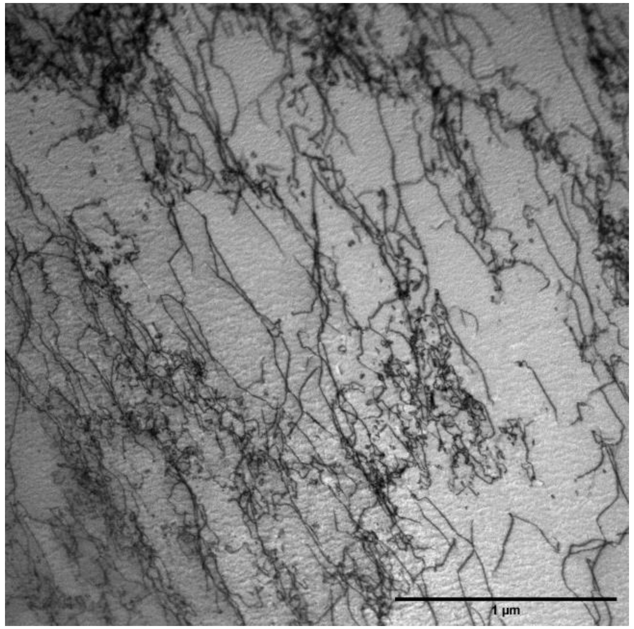


Edge dislocation with an extra plane of atoms [1]



Dislocation motion schematic [2]

- How to see dislocations? Transmission Electron Microscope (TEM)



Dislocations in a niobium single crystal

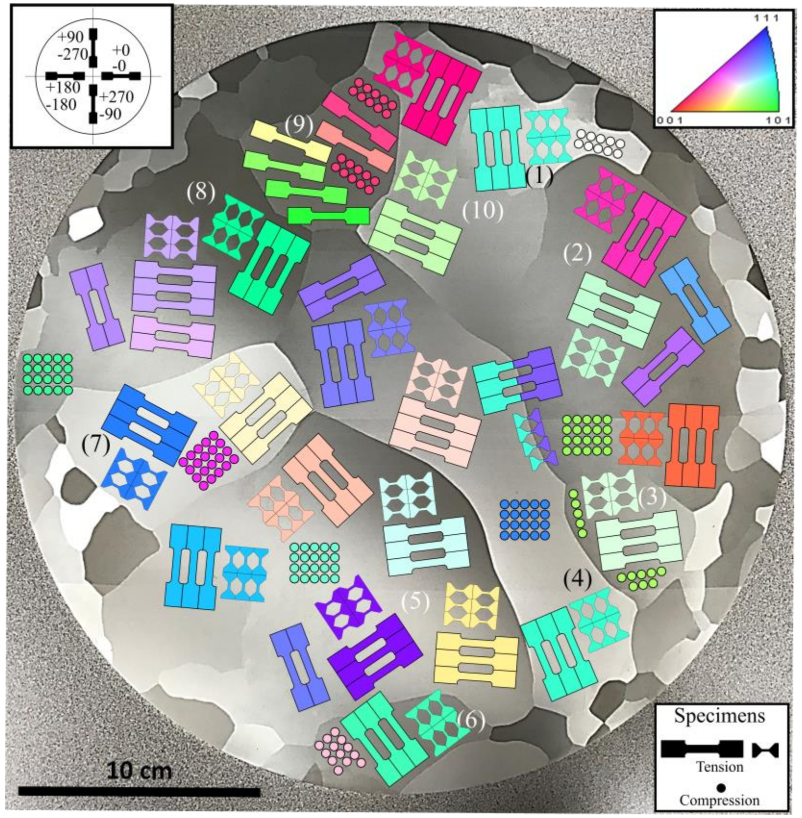
[1] https://www.tf.uni-kiel.de/matwis/amat/def_en/kap_5/illustr/i5_1_2.html
[2] https://imechanica.org/files/Lecture%208-%20Dislocation%20Motion.pdf

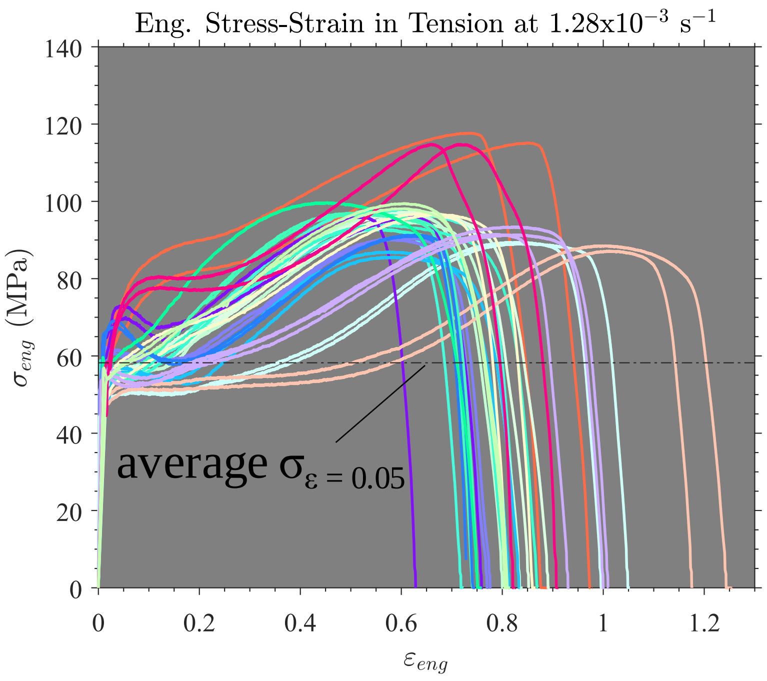
Mechanical Properties of Niobium Single Crystals

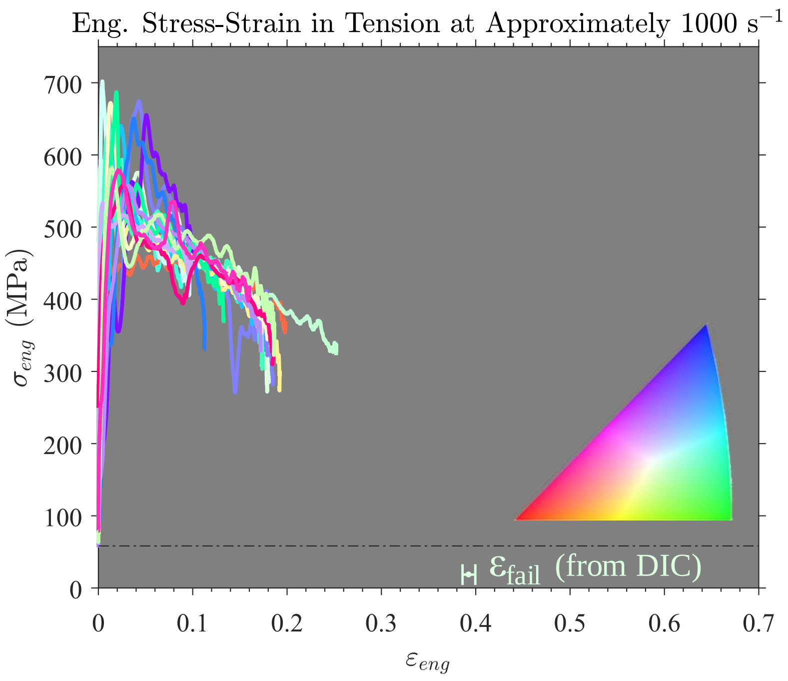
- Tensile and compression tests of single crystals with different crystal orientations and different strain rates

- Reduction of anisotropy at high strain rate in tension

J.-F. Croteau *et al.*, “Effect of strain rate on tensile mechanical properties of high-purity niobium single crystals for SRF applications,” *Materials Science and Engineering: A*, p. 140258, Sep. 2020, doi: [10.1016/j.msea.2020.140258](https://doi.org/10.1016/j.msea.2020.140258).

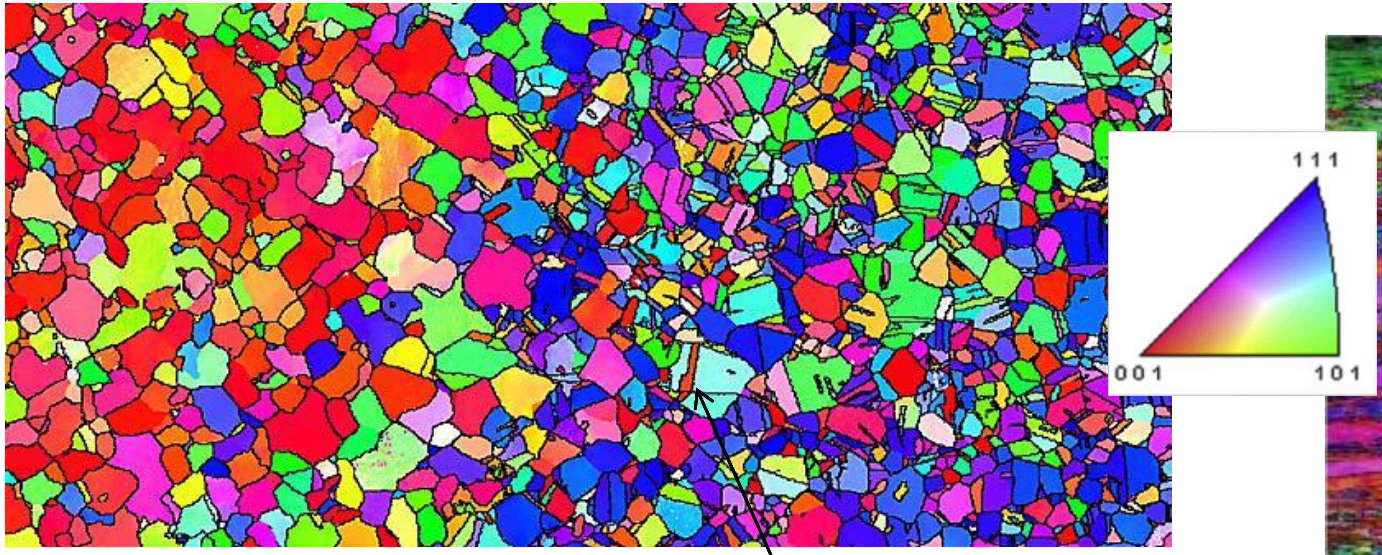




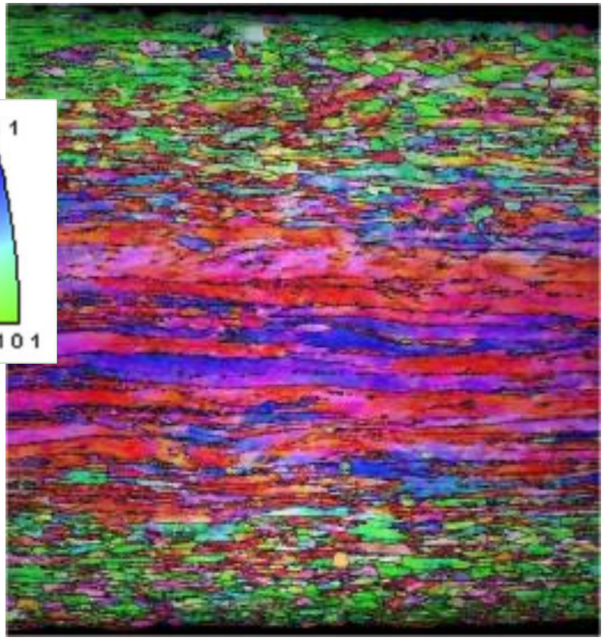


Electron Backscatter Diffraction (EBSD)

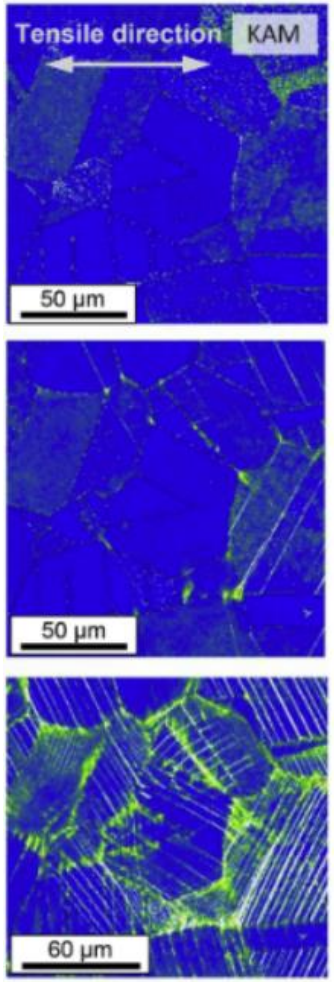
What can be extracted from EBSD data?
1. Orientation of grains
2. Grain size
3. Texture (leading to anisotropic sheet properties)
4. Local average misorientation



1. Grain orientations with twins [1]



3. Textured steel [2]

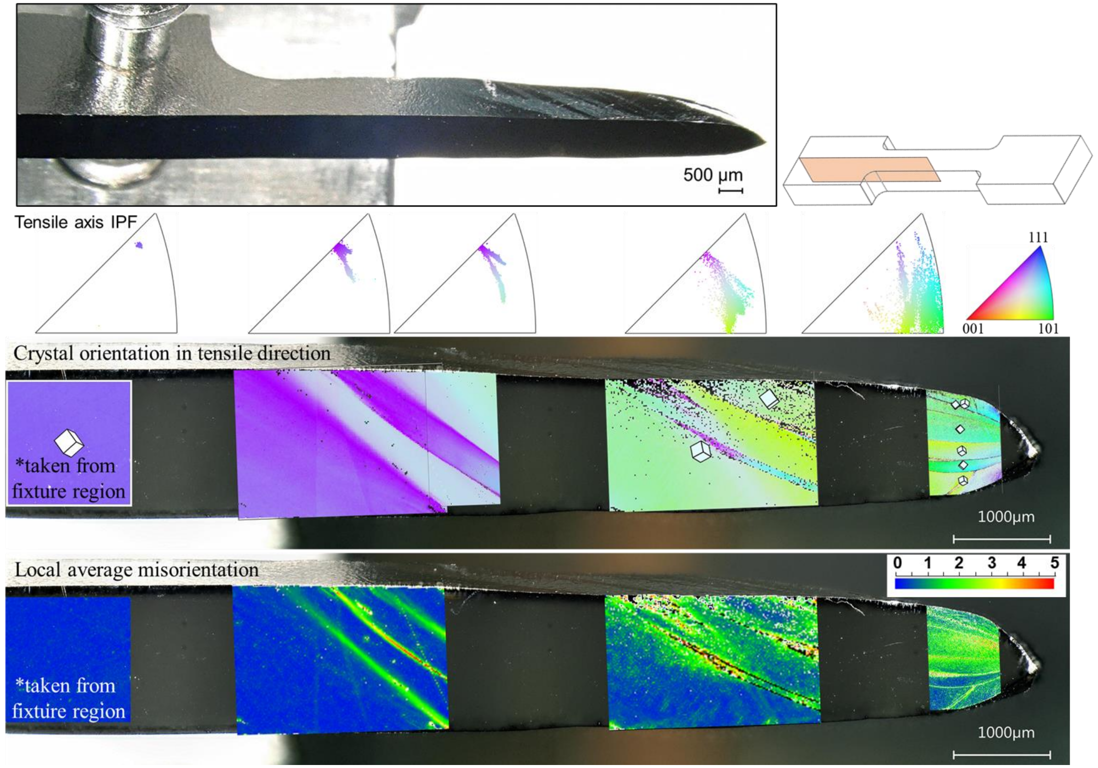


4. LAM/KAM [3]

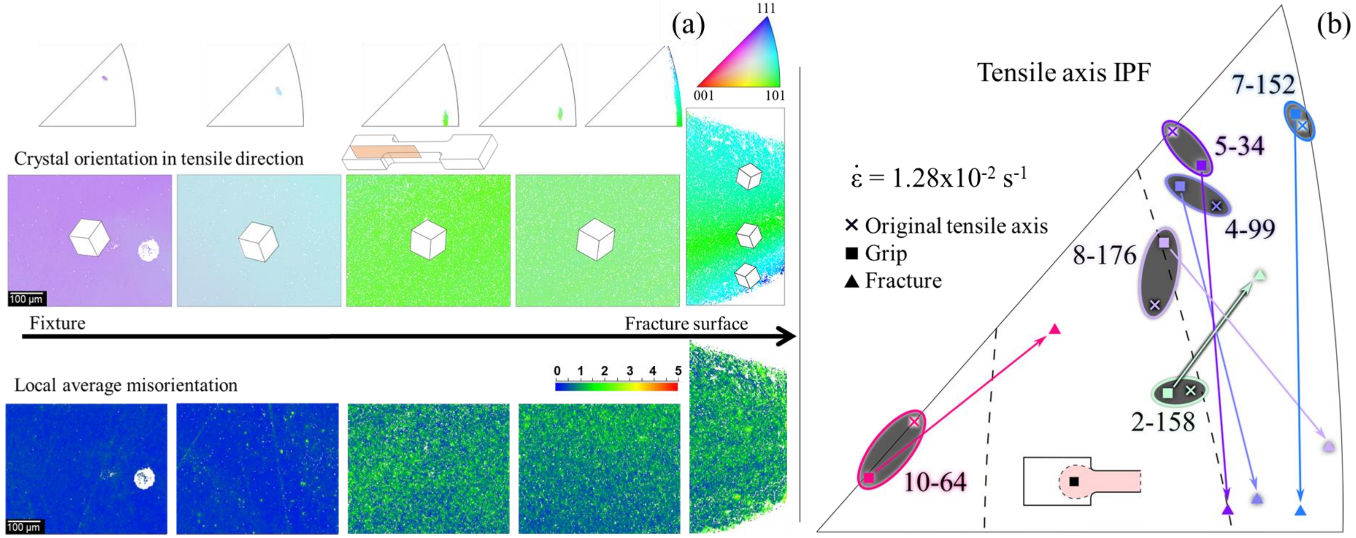
[1] https://www.plymouth.ac.uk/about-us/university-structure/faculties/science-engineering/electron-microscopy-centre/electron-backscatter-diffraction-ebsd
[2] http://www.dierk-raabe.com/ebsd-and-3d-ebsd/
[3] https://doi.org/10.1016/j.jnucmat.2019.01.034

Mechanical Properties of Niobium Single Crystals

- EBSD analysis of the cross-section of niobium single crystals
- Different microstructures observed after deformation for different crystal orientations
  - Related to dislocation motion

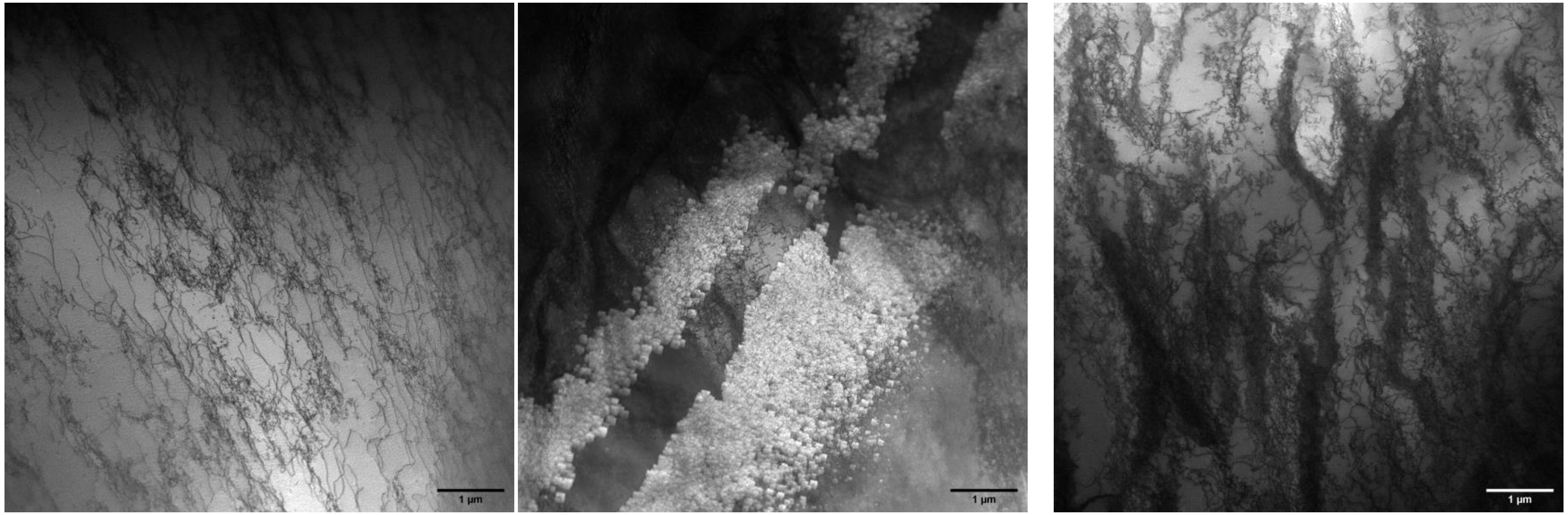


J.-F. Croteau *et al.*, "Effect of strain rate on tensile mechanical properties of high-purity niobium single crystals for SRF applications," *Materials Science and Engineering: A*, Sep. 2020, doi: 10.1016/j.msea.2020.140258.

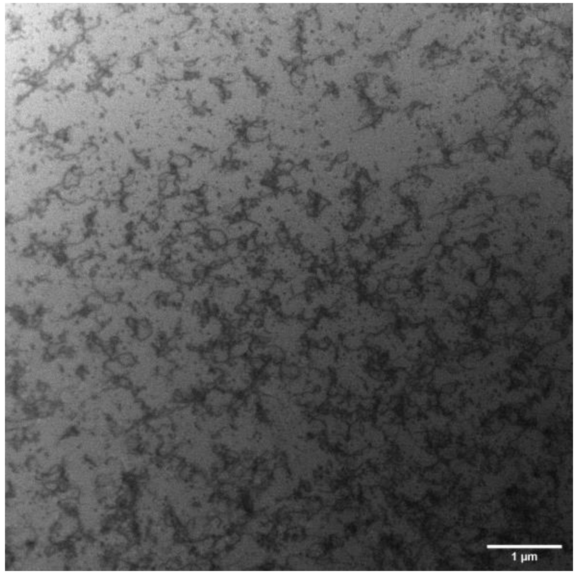


Mechanical Properties of Niobium Single Crystals

- Large difference in the dislocation substructure between low and high strain rate
- Short dislocations, small loops and a homogeneous distribution at high strain rate
  - This likely confirms the activation of multiple slip systems and the reduced anisotropy



Low strain rate specimens – Alignment of dislocations, cell walls, high density



High strain rate – No alignment, short segments and loops

Conclusions and Future Work

Outline

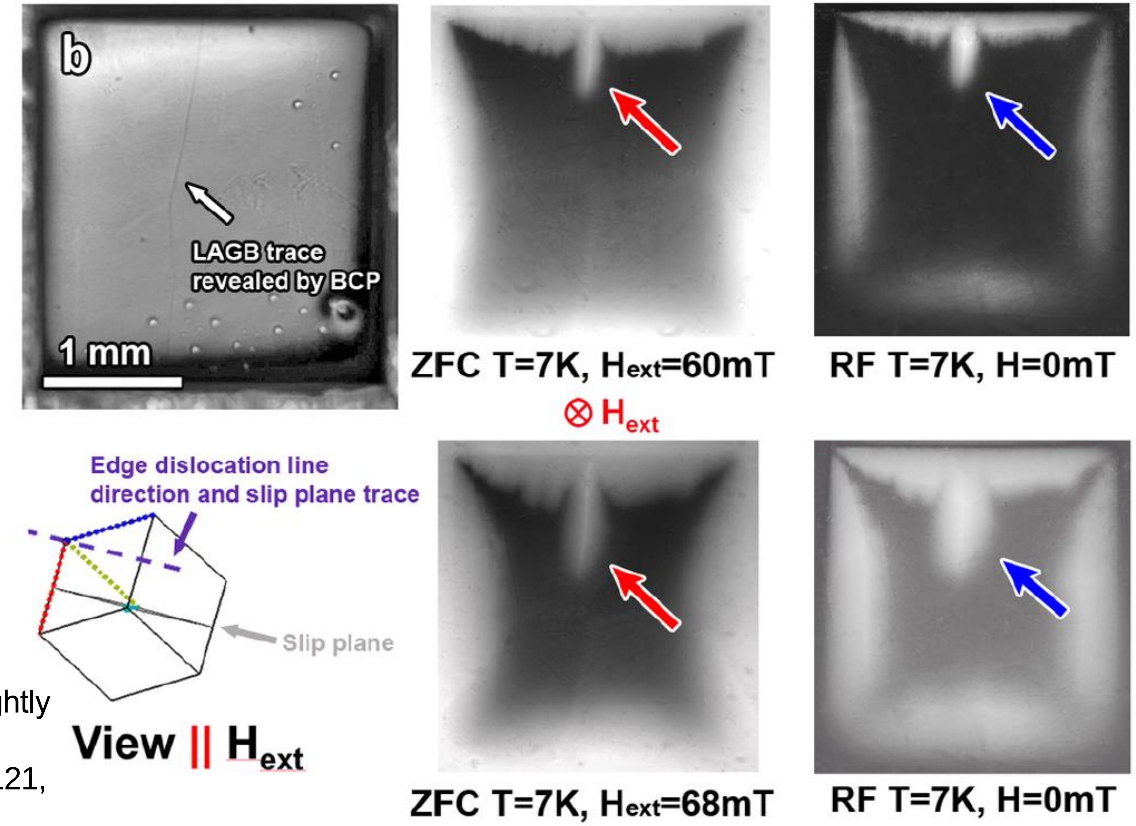
- SRF cavity fabrication
- Sheet forming with electro-hydraulic forming
- Characterization of copper and niobium
  - Properties of electron beam welded specimens
  - Properties of niobium single crystals
- Conclusions and future work

Conclusions and Future Work

- Characterization of the mechanical properties is essential for accurate sheet forming prediction in finite element models
- Strain rate sensitivity
  - FCC metals: low (copper)
  - BCC metals: high (niobium)
- Reduction of anisotropy and ductility for niobium single crystals deformed at high strain rate
- Different microstructures for different strain rates and crystal orientations

Future Work

- Effect of the different dislocation substructures on the superconducting properties
(National High Magnetic Field Laboratory - NHMFL)

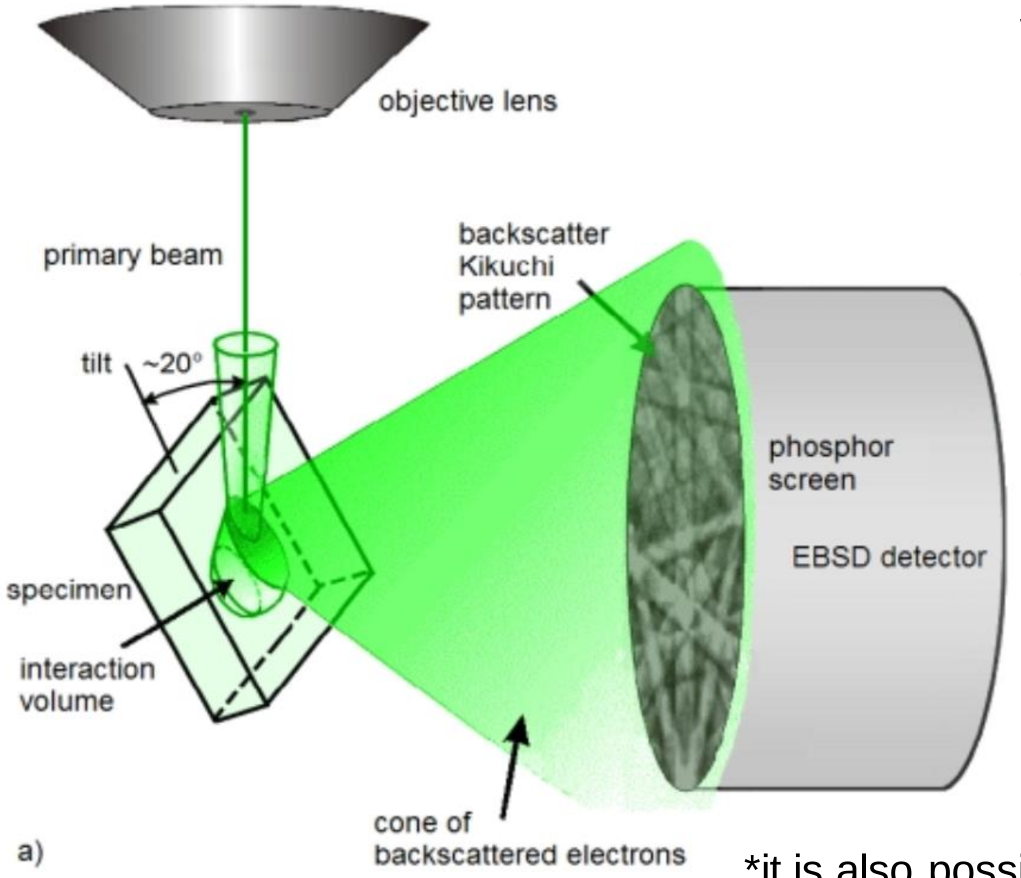


Z.-H. Sung *et al.*, "Development of low angle grain boundaries in lightly deformed superconducting niobium and their influence on hydride distribution and flux perturbation," *Journal of Applied Physics*, vol. 121, no. 19, p. 193903, May 2017, doi: 10.1063/1.4983512.

Additional Slides

Electron Backscatter Diffraction (EBSD)

- EBSD is used to measure the orientation of a crystalline material for a “volume of material” using reflected electrons and a scanning electron microscope (SEM)



Schematic of EBSD in an SEM [1]

What can be extracted from EBSD data?

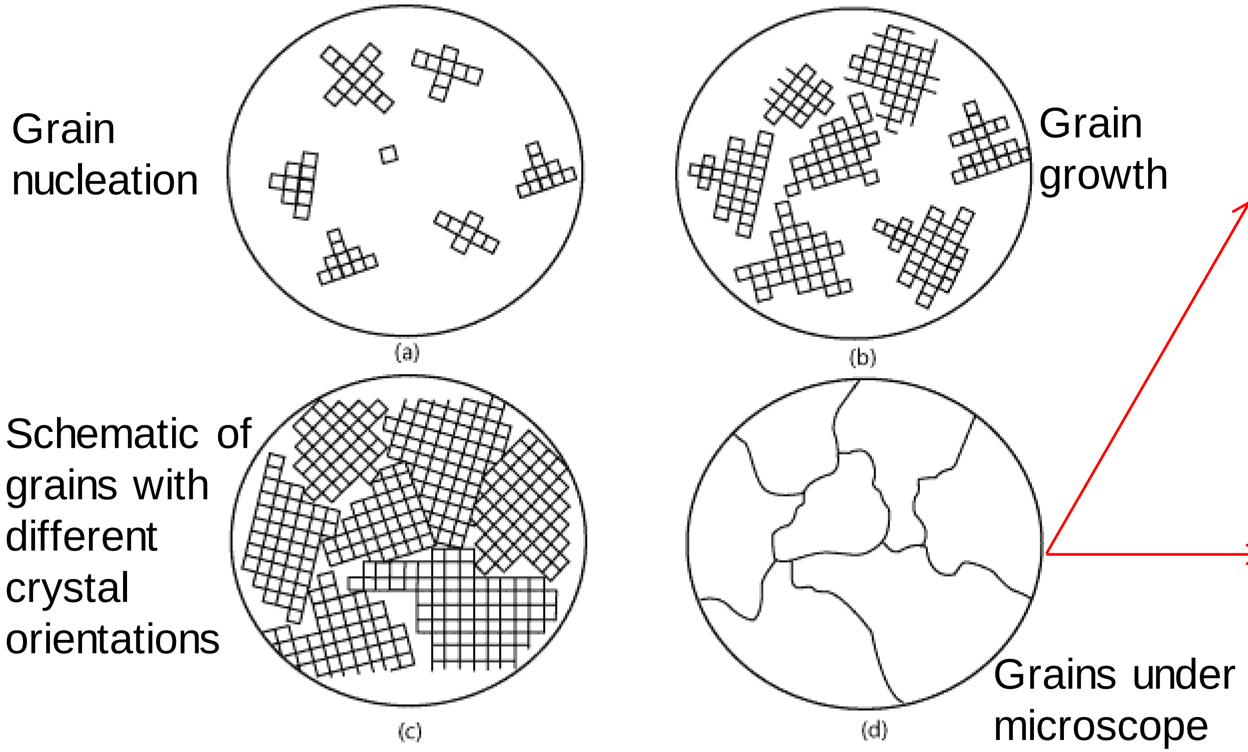
1. Orientation of grains
2. Grain size
3. Texture (leading to anisotropic sheet properties)
4. Local average misorientation

*it is also possible to measure the orientation of a crystal using a transmission electron microscope (TEM)

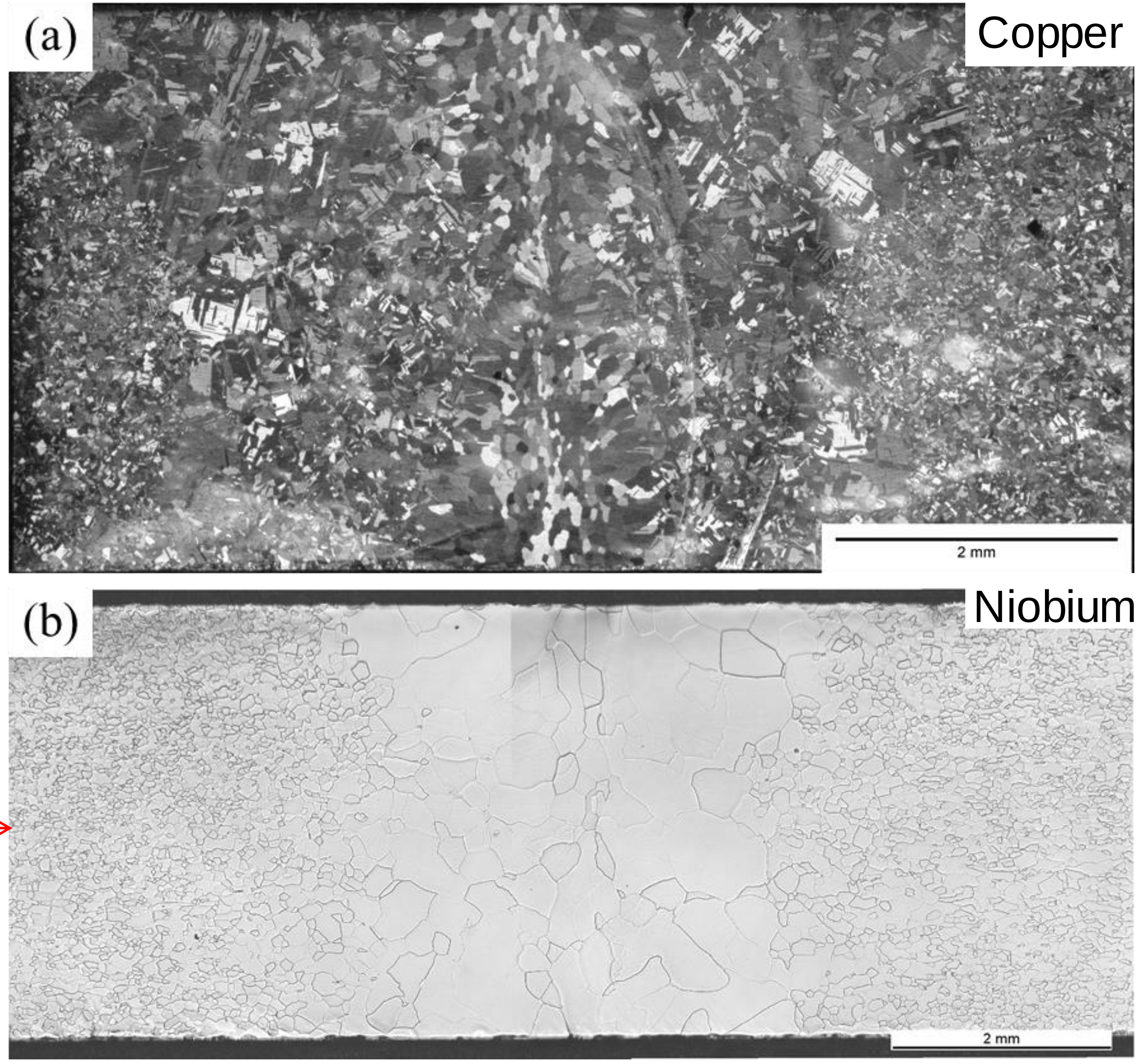
[1] http://www.ebsd.info/tkd.htm

Properties of Electron Beam Welds at High Speed

- How to obtain these results?
  1. Mechanical polishing (mirror finish)
  2. Chemical etching (reveals grain boundaries)
  3. Optical microscope



Solidification steps in metals



https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/solidification.htm