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Materials Microstructures: Your #1 Source for Uncertainty in Component Properties

- or -

How I Learned to Stop Worrying and Love Materials Science

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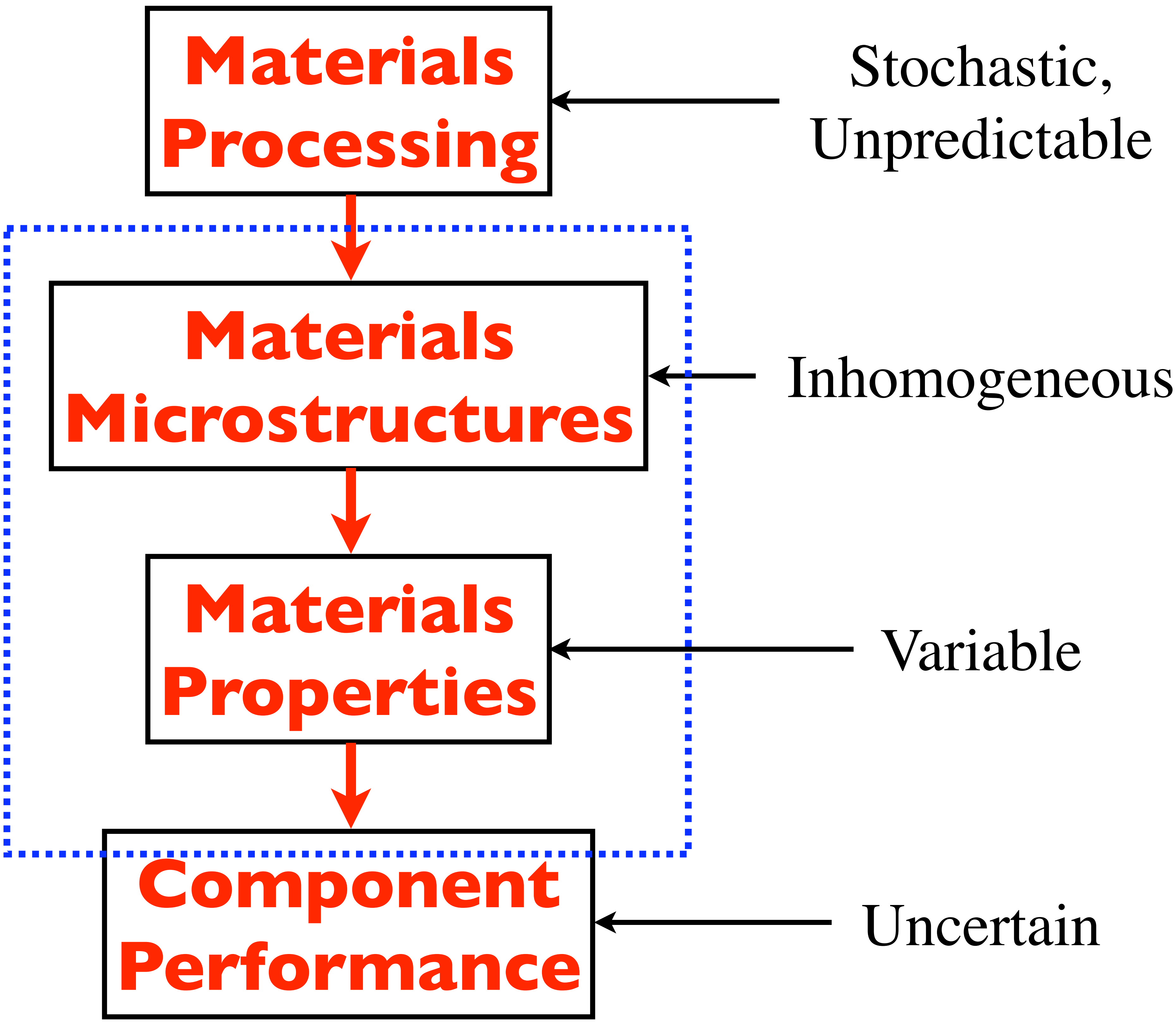
Introduction

- No two devices / parts / components behave identically.
- Uncertainty in component behavior has several sources.
- Most components are made of materials.
- Most materials have internal (micro-)structures.
- Processing imparts microstructure variations.
  - Processing is not truly repeatable.
  - Process conditions are not uniform (in space / time).
  - Most materials naturally form inhomogeneously.
- Microstructures evolve with time (i.e. "age").
- Microstructure variations produce property variations.
- Materials property variations lead to component property variations.
- No two devices / parts / components behave identically.

Introduction

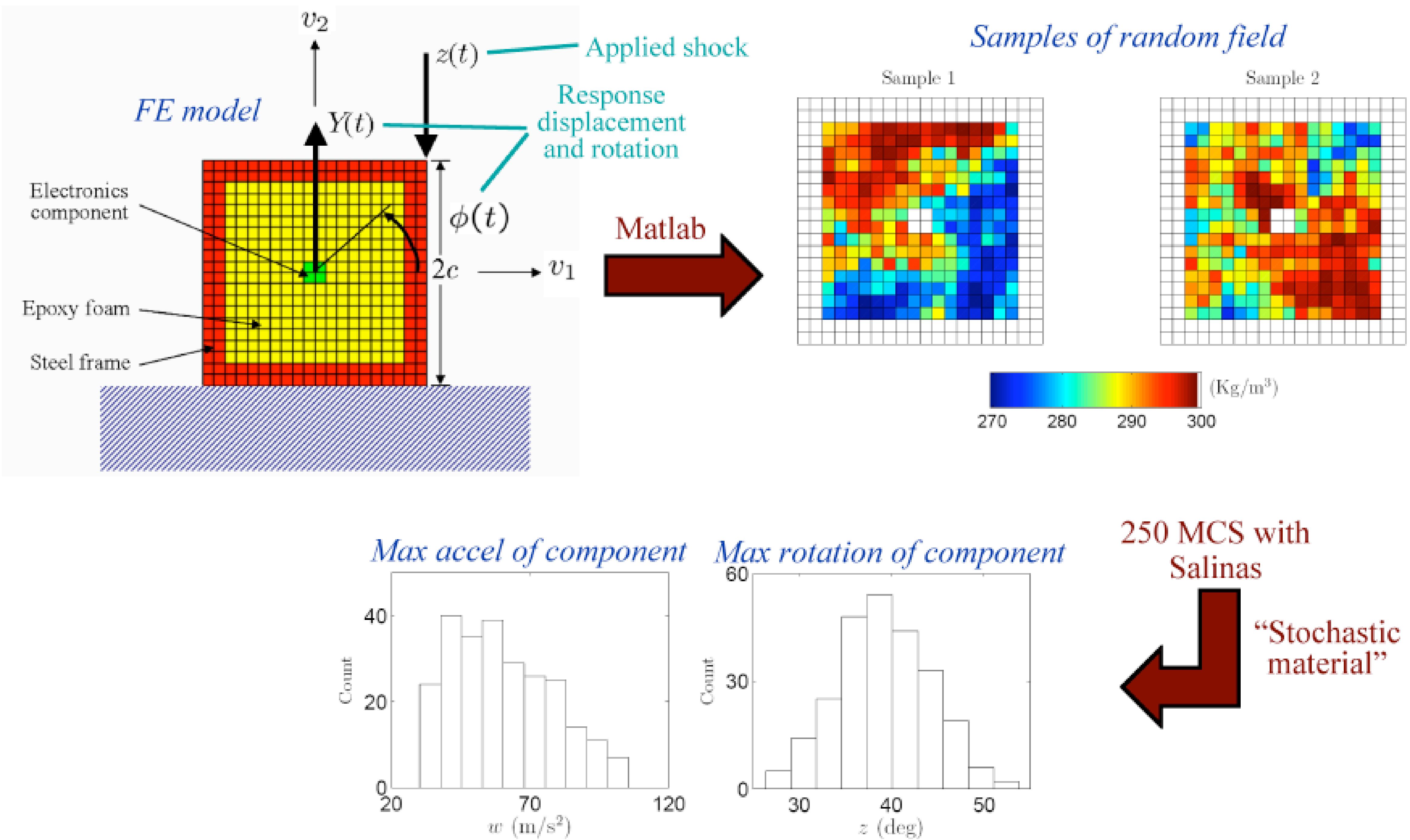


Outline

- Example of ongoing "component QMU" research
- Examples of microstructure-induced variability:
  - Inhomogeneity in materials microstructures
  - Variability in materials properties
- Examples of "toy" simulation problems:
  - Polycrystalline elastic Si cantilever
  - Two-phase conductor
- Generalized simulation procedure
- Summary

QMU in Component Performance

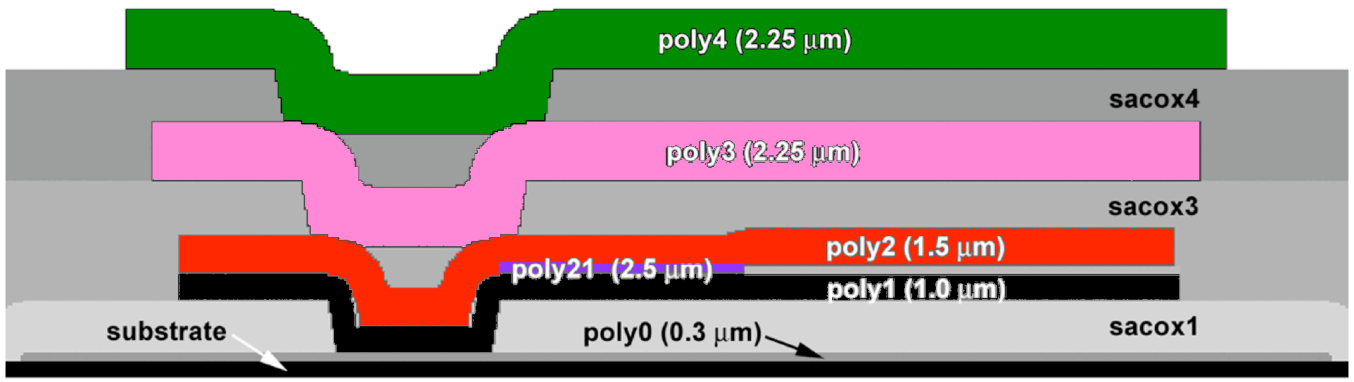
Density variations in EF-AR20 epoxy foam:



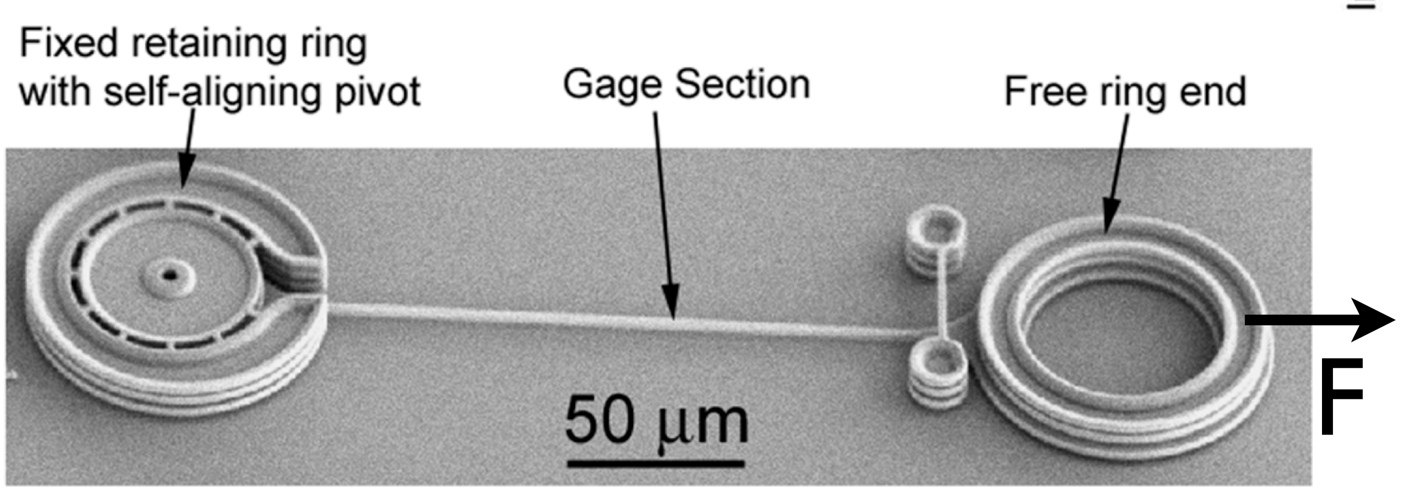
R.V. Field, private communication.

Variability in Failure Strength of PolySi

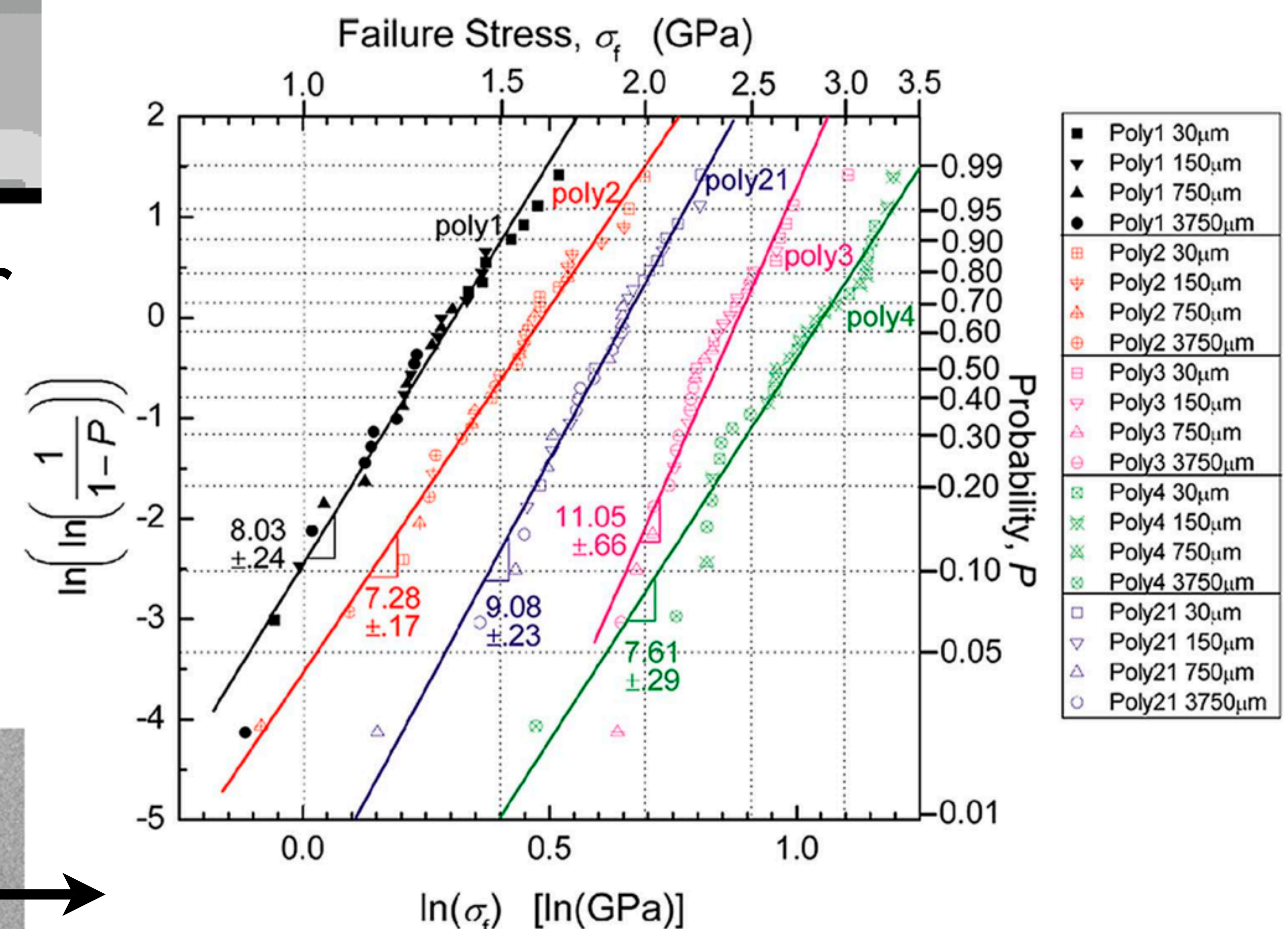
Surface flaws produce variability in failure behavior:



SUMMiT V™ Notional Multilayer Cantilever Assembly



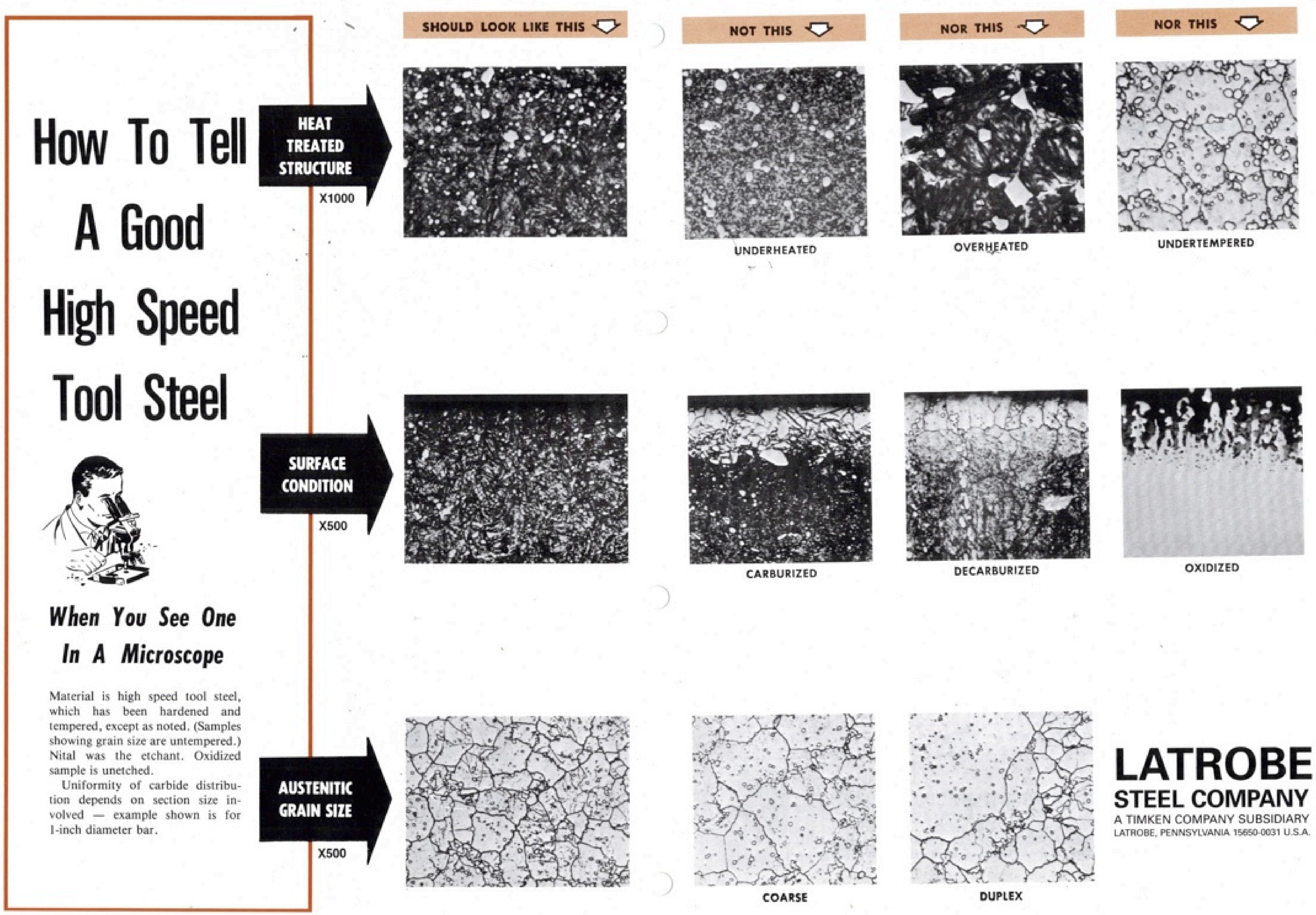
Tensile Test



Weibull Statistics

B.L. Boyce, J.M. Grazier, T.E. Buchheit, and M.J. Shaw, *J. MEMS* **16** (2007) 179.

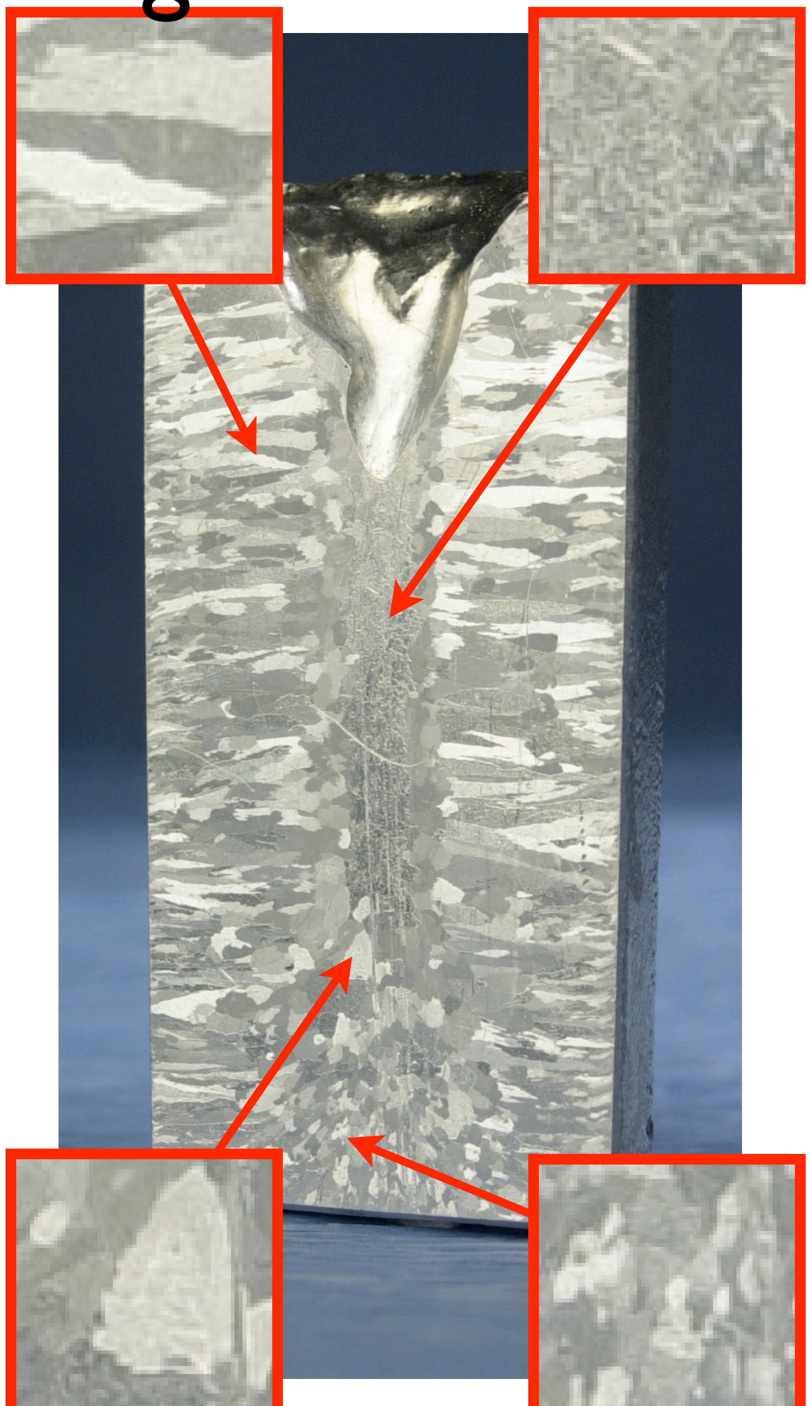
Microstructure Variations in Tool Steels

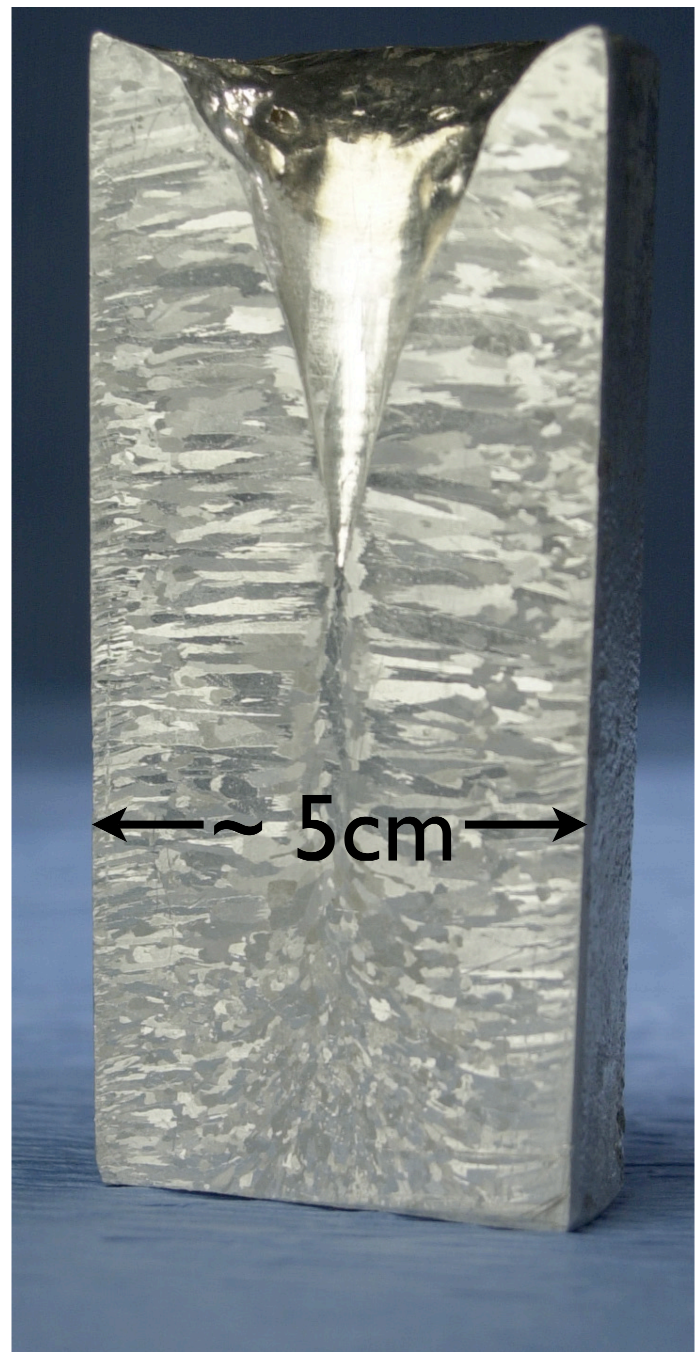


CryoKing, http://www.cryoking.co.in/site/links.html.

Pure Aluminum Ingots

Nonuniform solidification produces large inter- and intra-ingot microstructure (and compositional) variations:

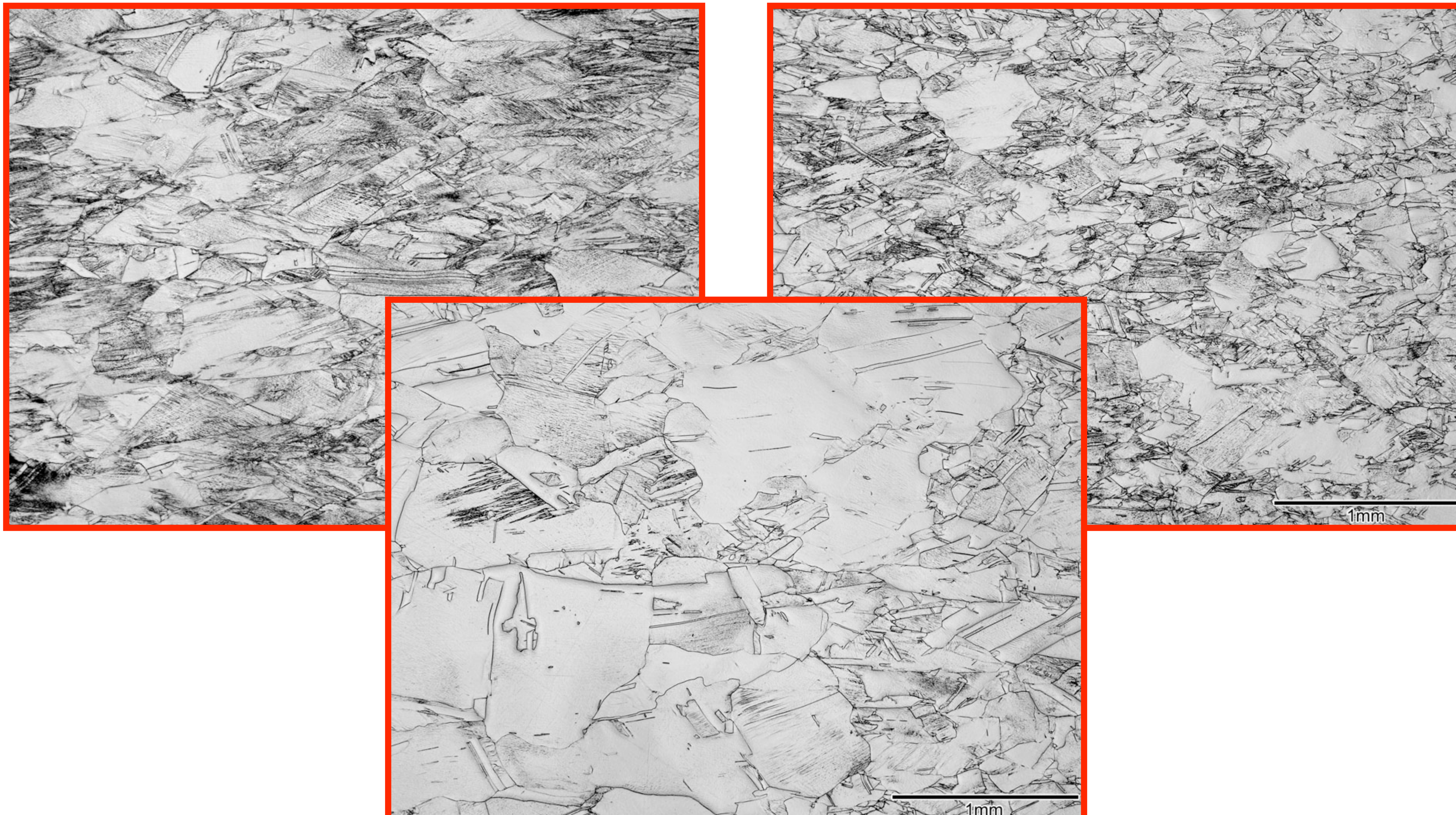




H.K.D.H. Bhadeshia, http://www.msm.cam.ac.uk/phase-trans/2001/slides.IB/photo.html.

Forged Copper Bar

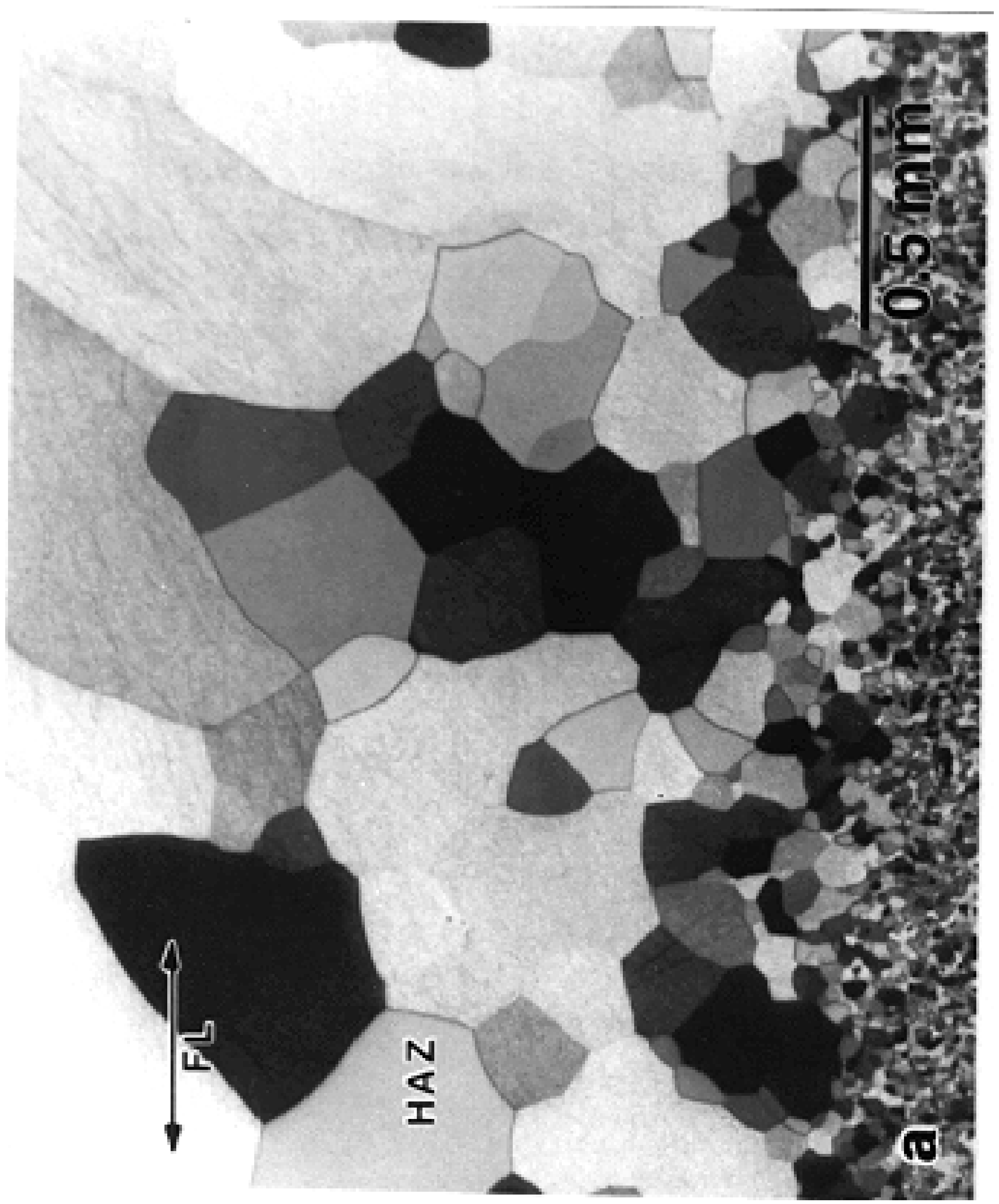
More microstructure variations within a single part:



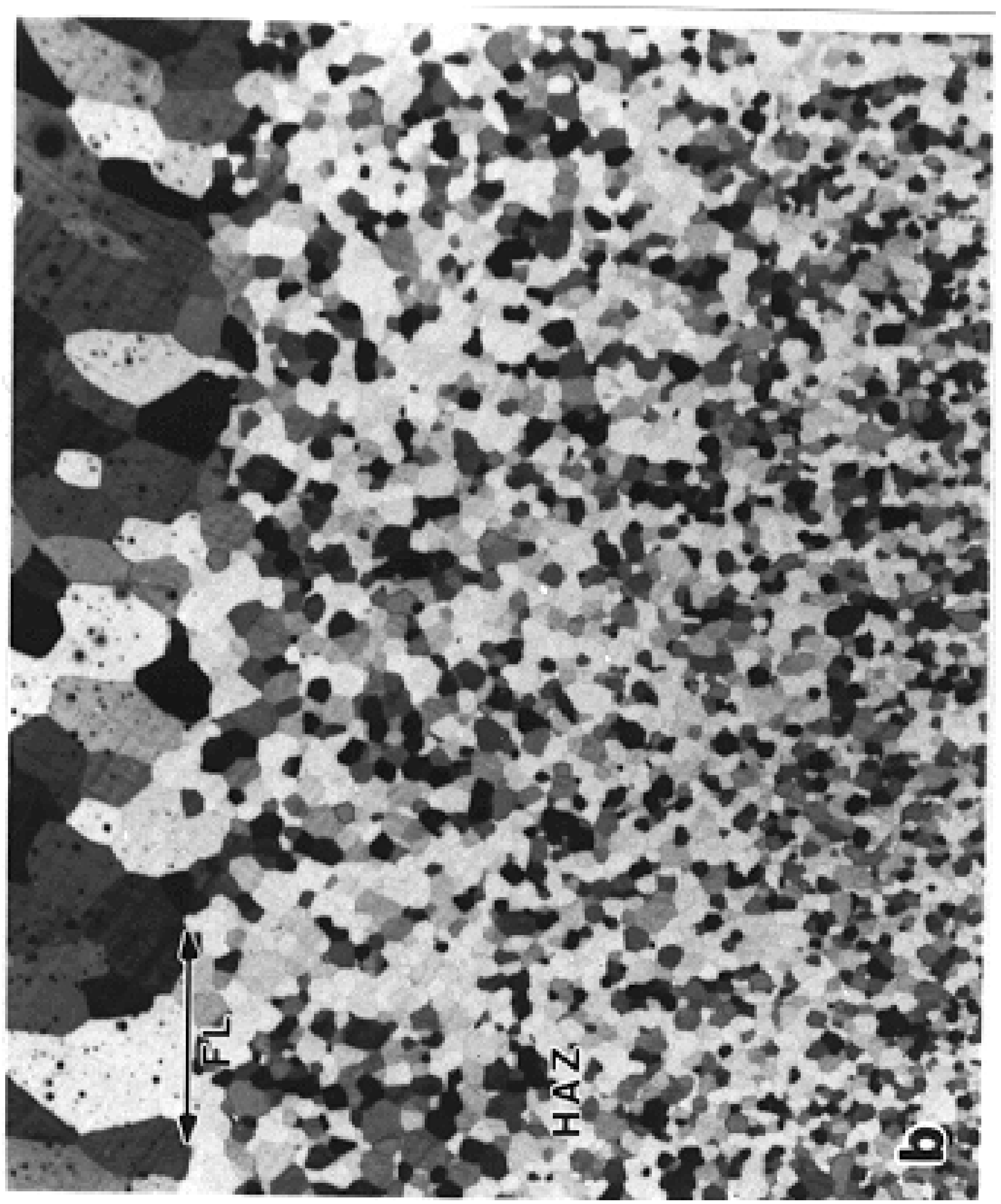
L.N. Brewer, B.L. Boyce, and A.C. Kilgo, private communication.

HAZ* in Molybdenum Welds

Impurities dramatically affect weld microstructures:



Pure Mo



w/ Oxide Particles

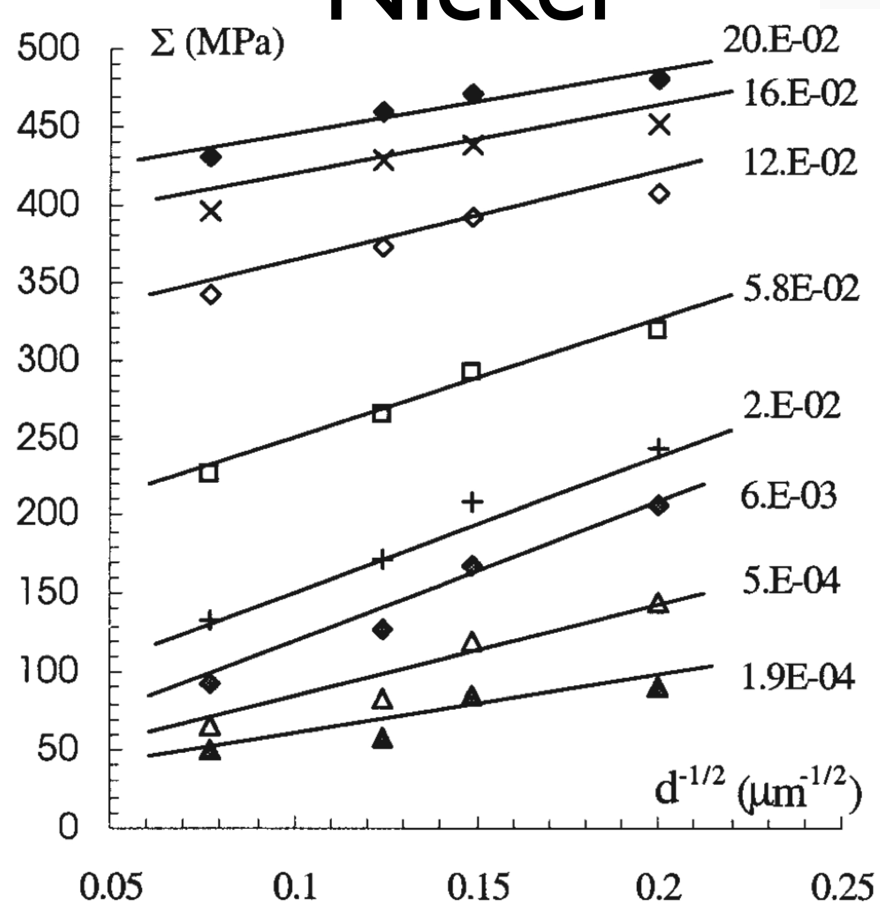
C.V. Robino and E.A. Holm, private communication.

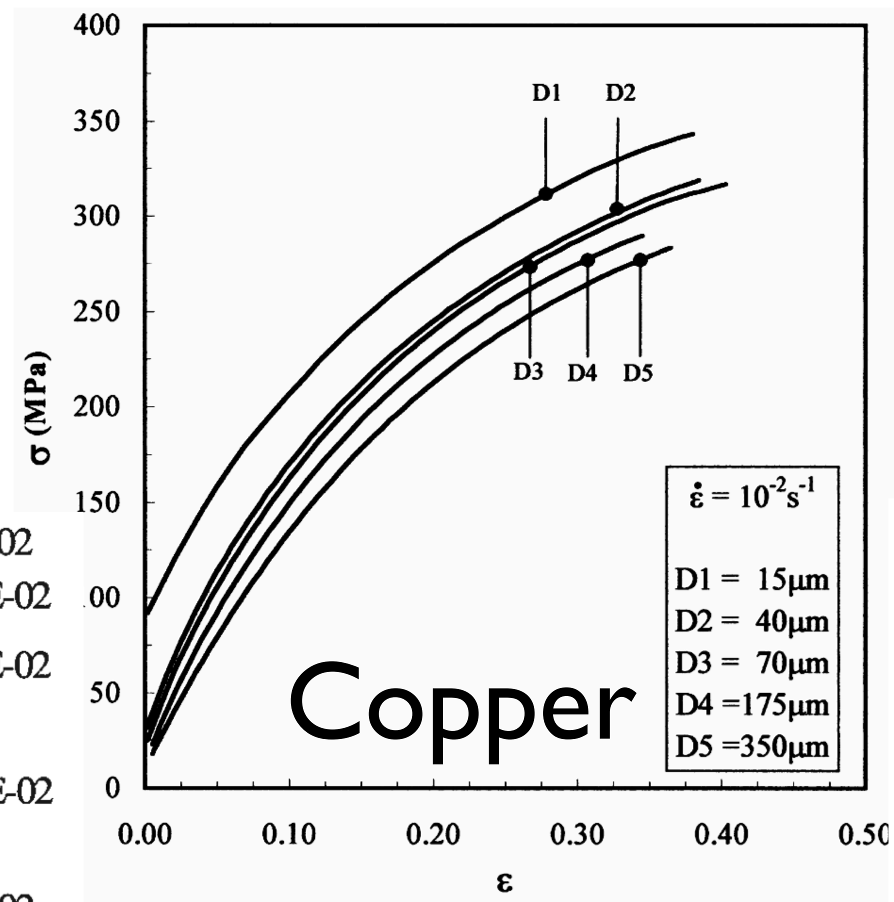
* Heat-Affected Zone

Hall-Petch Effect in Metals

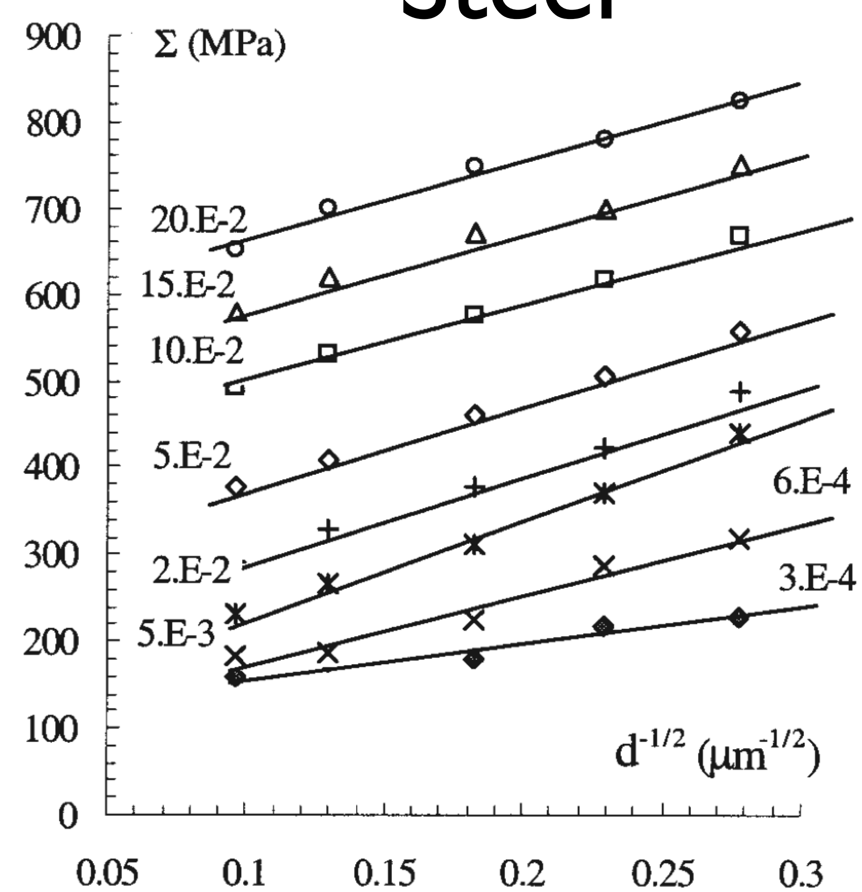
The yield strength of a metal depends on its grain size:

Nickel



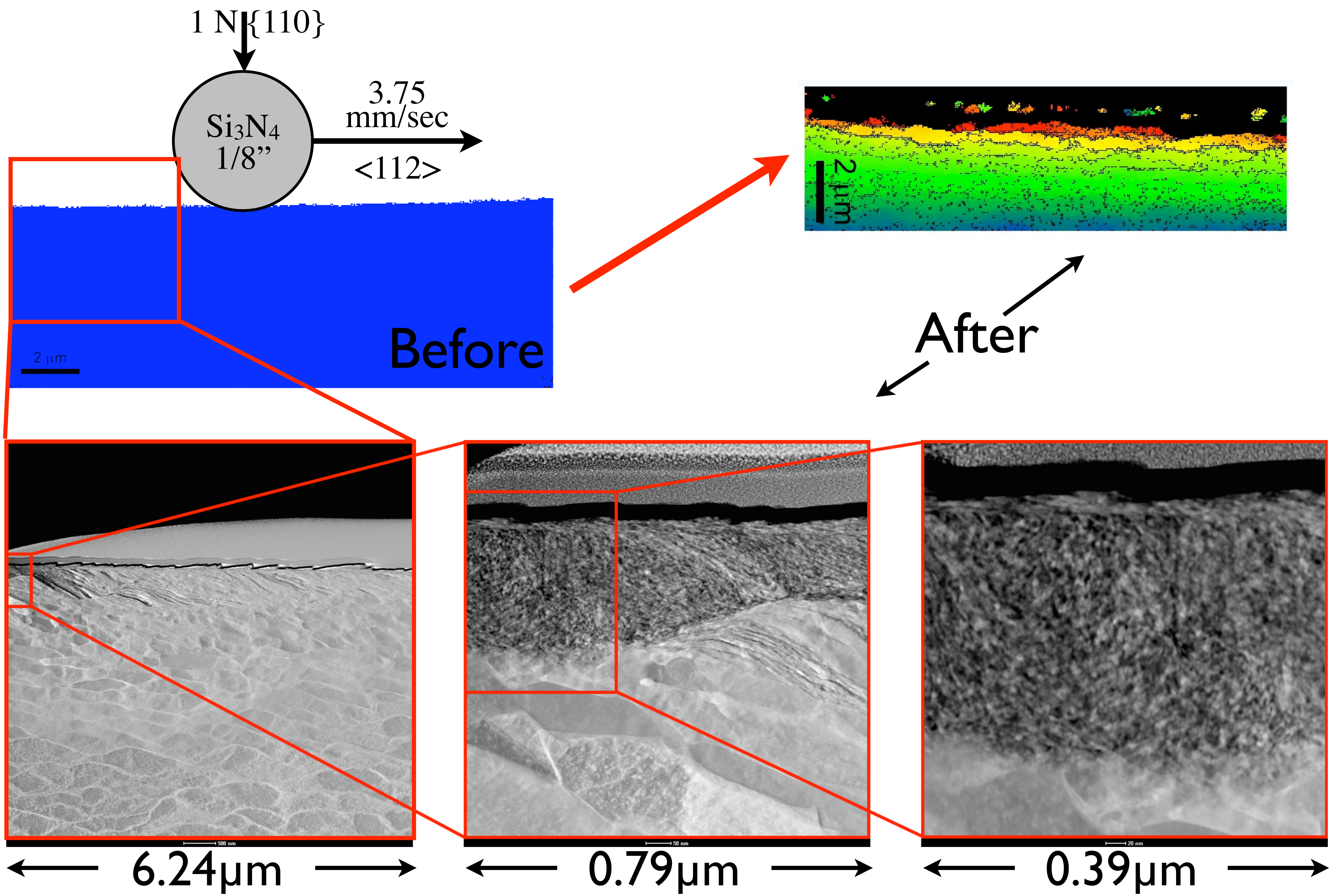


Stainless Steel



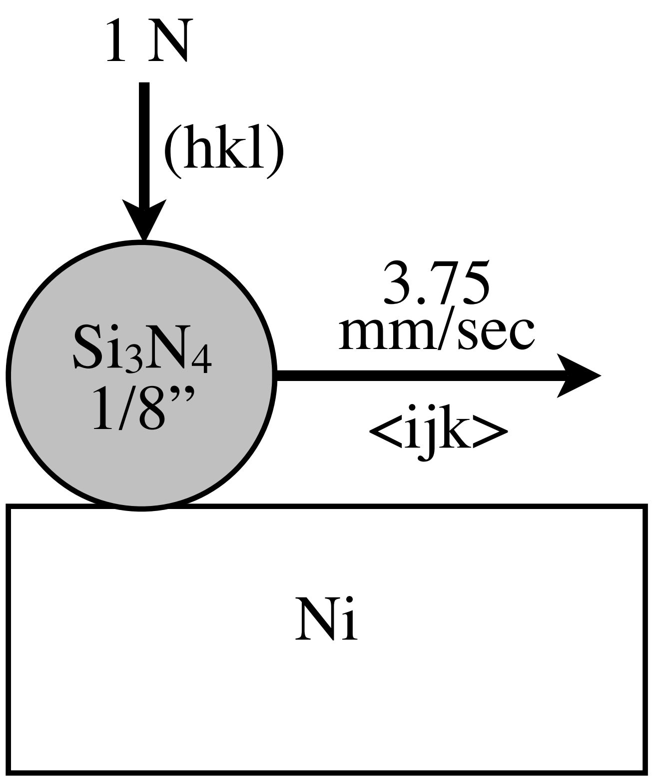
J.V. Fernandes and M.F. Vieira, *Acta Mater.* **48** (2000) 1919.
X. Feaugas and H. Haddou, *Met. Trans. A* **34A** (2003) 2329.

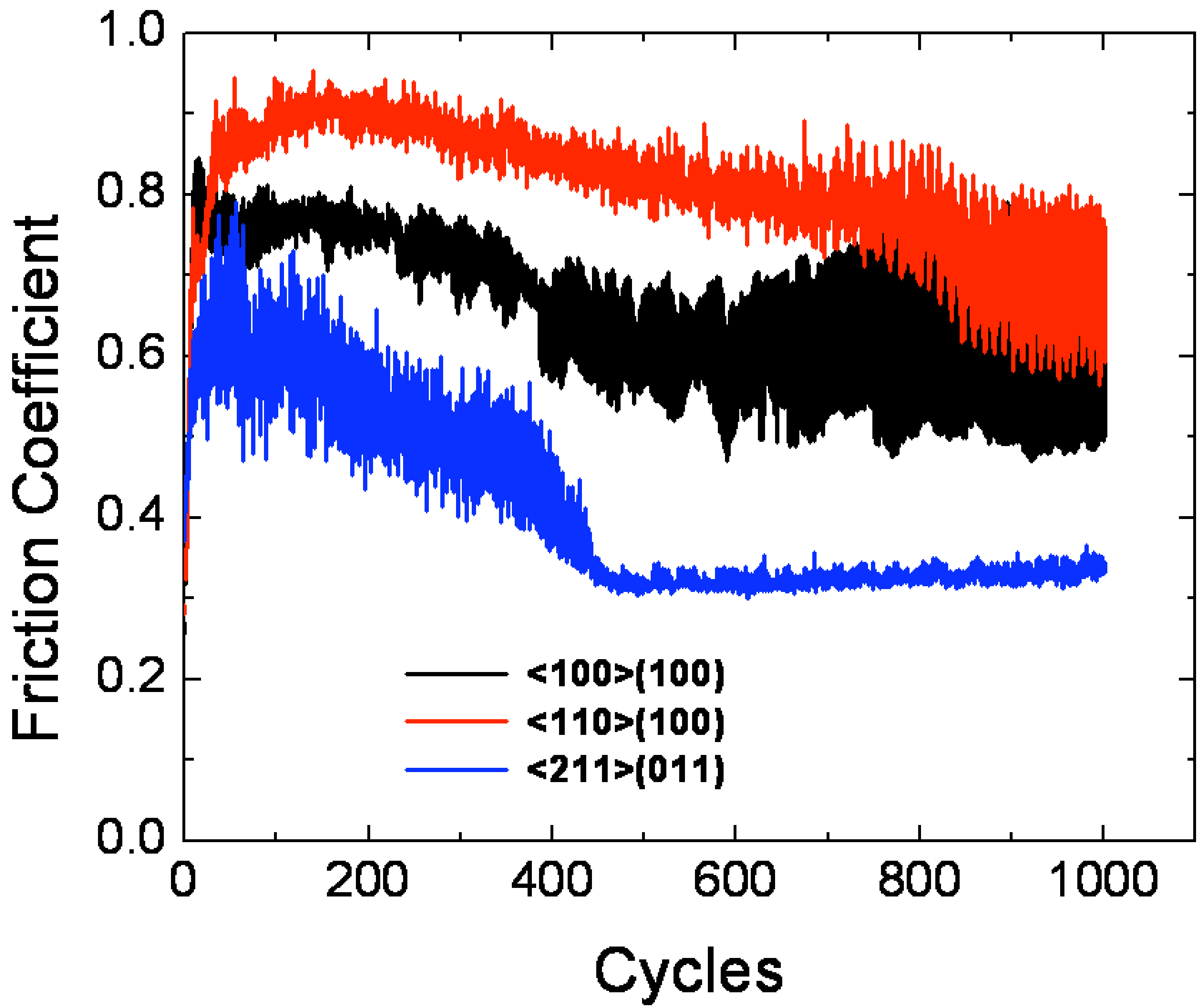
Wear of Nickel Single Crystals



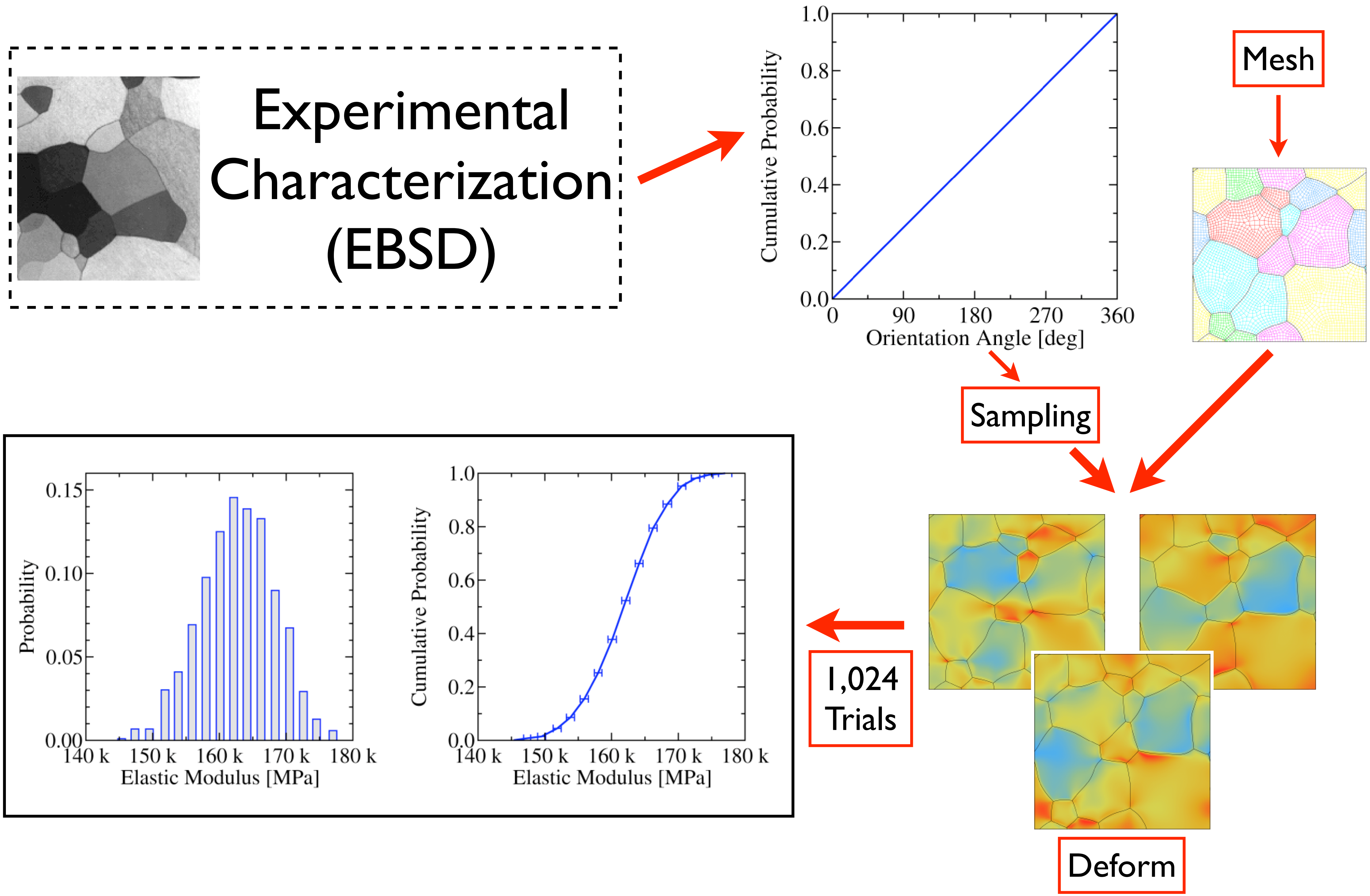
Friction of Nickel Single Crystals

Crystallographically-sensitive wear leads to lubrication:

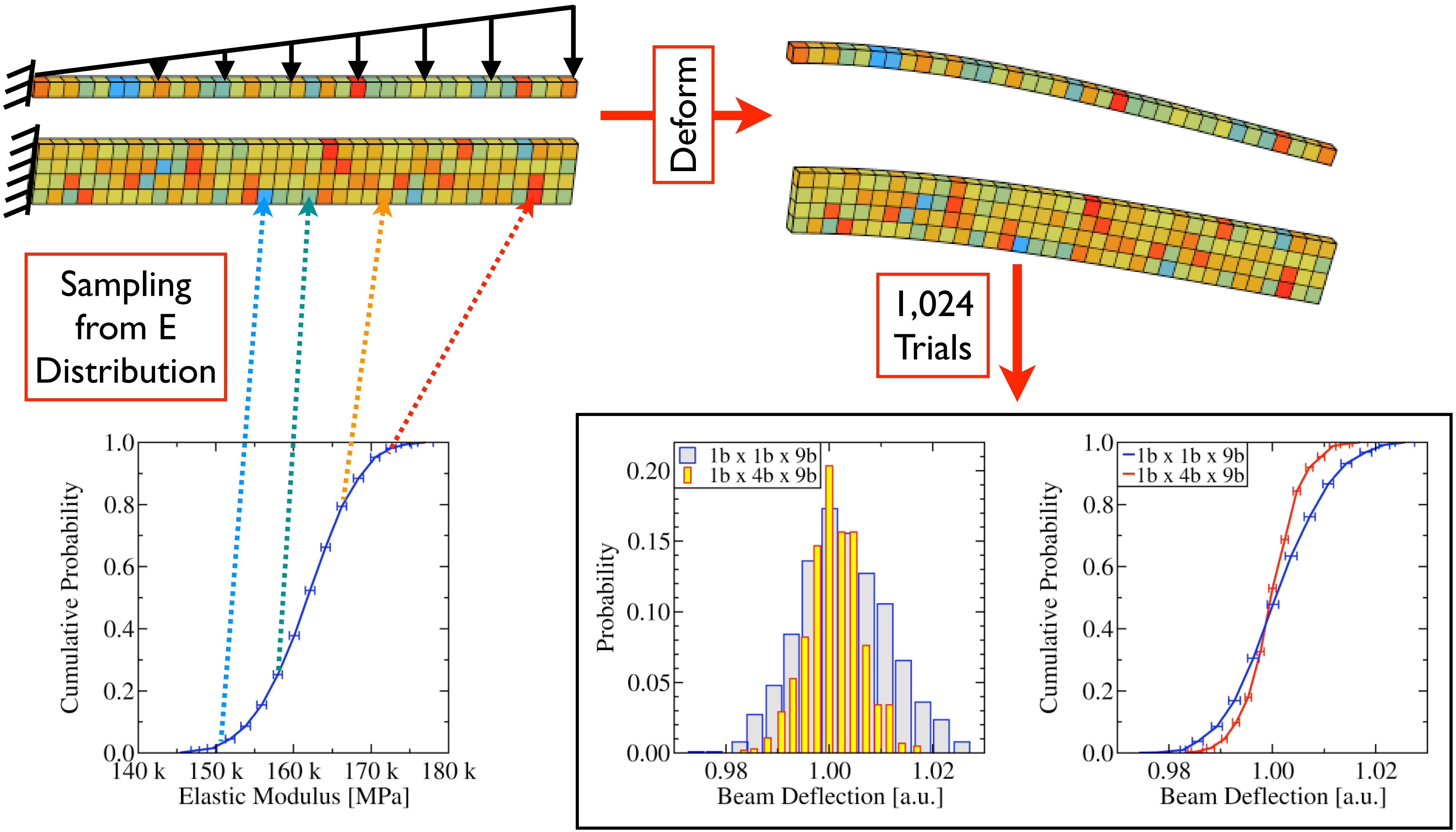




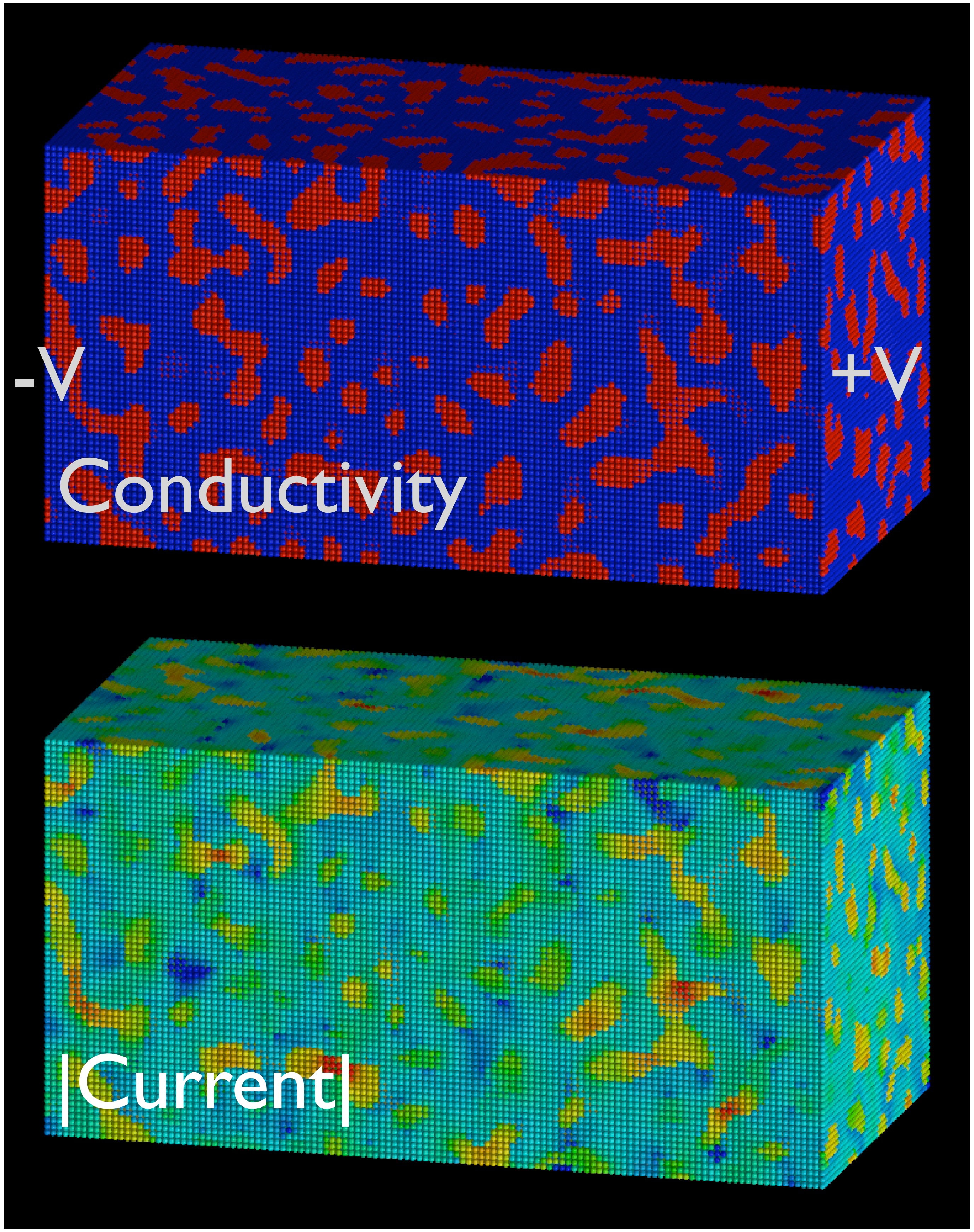
Example 1A: Elastic Polycrystal

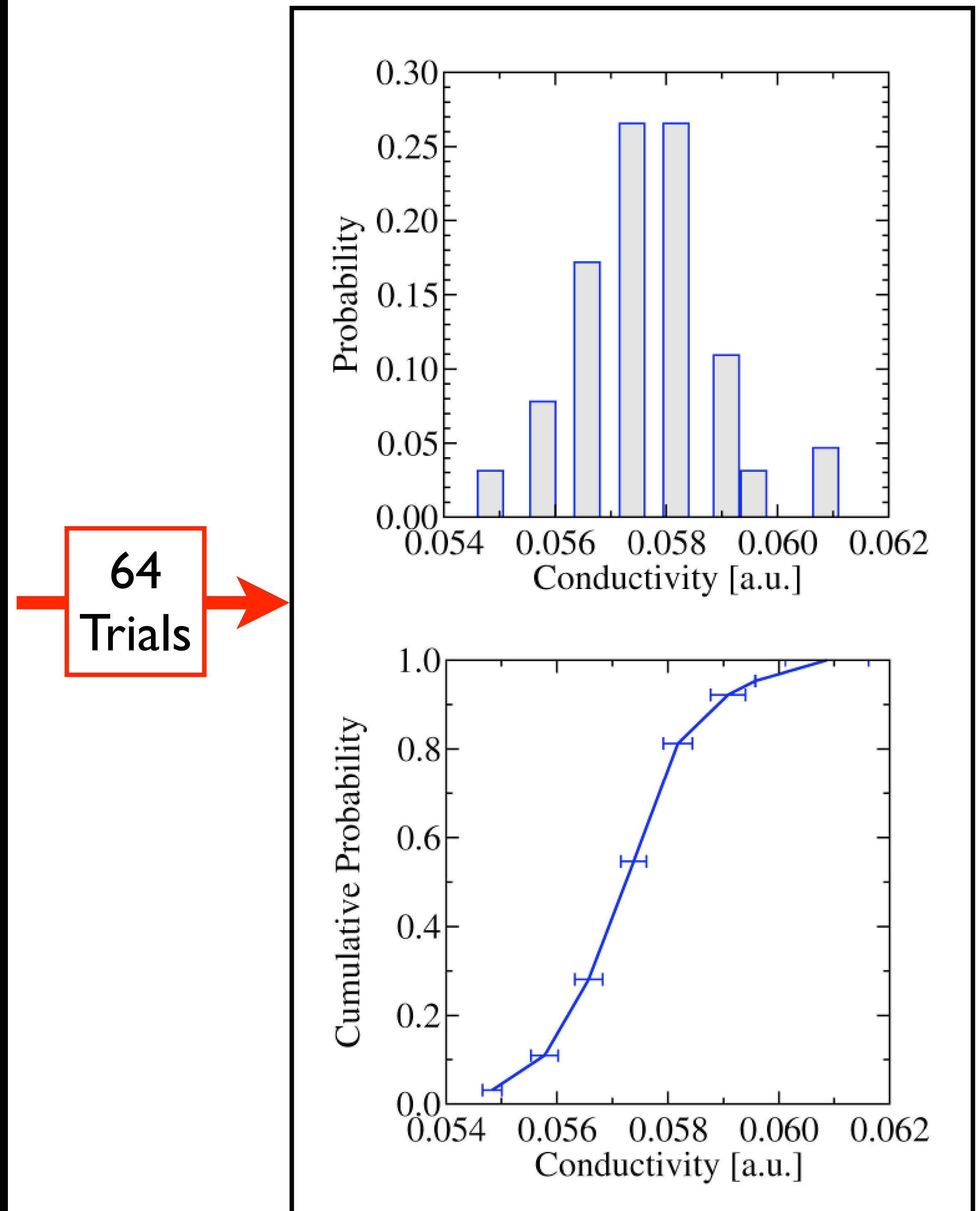


Example 1B: Elastic Cantilever

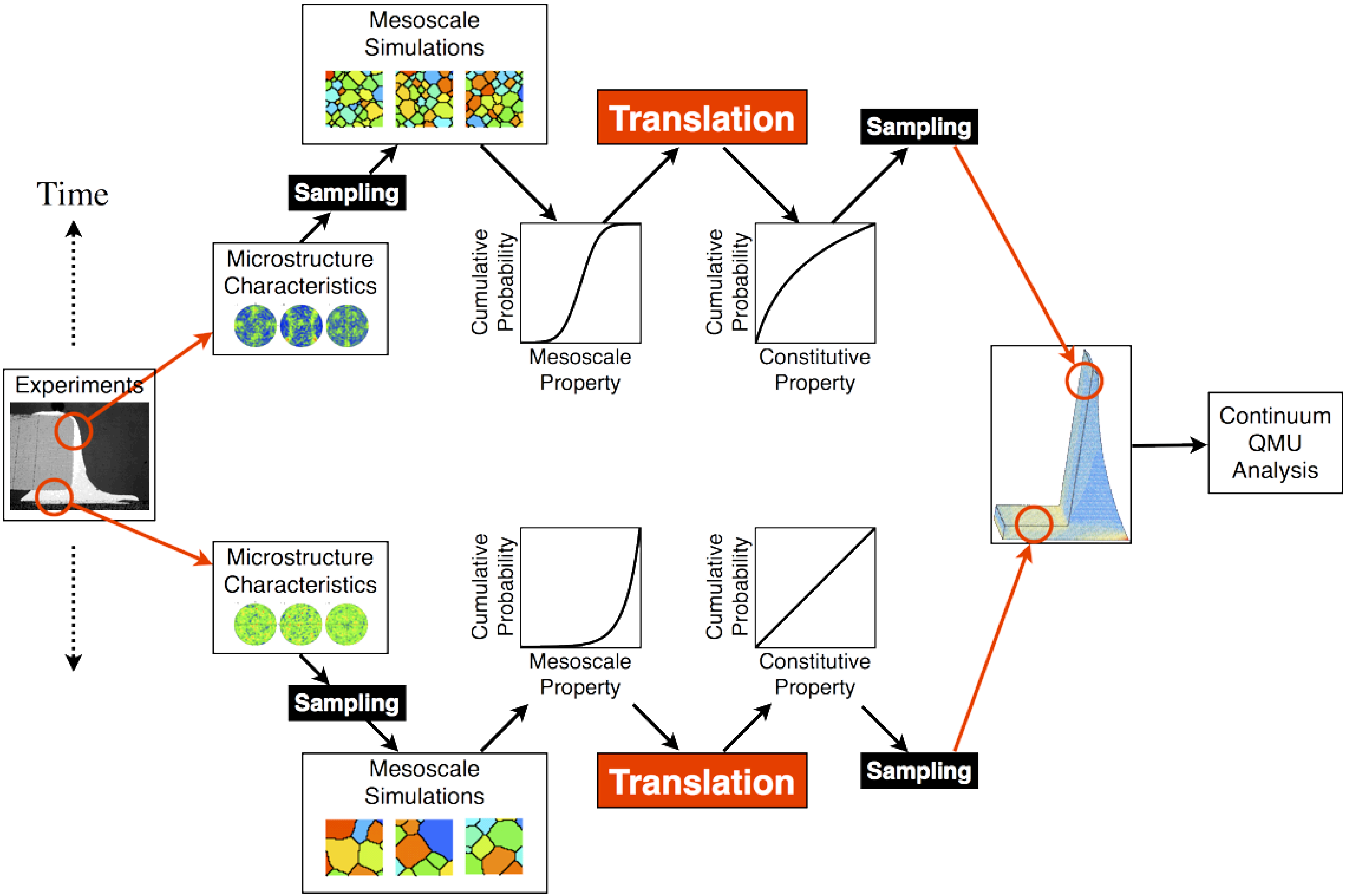


Example 2: Two-Phase Conductor





Generalized Analysis Procedure



Challenges

- Translating microstructural statistics to the continuum scale is not usually so straightforward:
  - Microscale Cond. → Macroscale Cond. = trivial
  - Microscale Elasticity → Beam Deflection = easy
  - Microscale Plasticity → Fatigue Life = hard
- Microstructural length scale must correspond to continuum domain resolution:
  - Statistics are scale- (i.e. population-) dependent.
  - Potential source of computational limitation.
- Microstructural features can act in two ways:
  - Collectively (e.g. texture → deformation).
  - Critically (e.g. flaws → failure, percolation → cond.).

Summary

- No two devices / parts / components behave identically.
- Most materials have internal (micro-)structures.
- Processing and aging impart microstructure variations.
- Microstructure variations produce property variations.
- Materials property variations lead to
  significant uncertainty in component performance
  (depending on scales and population sizes).
- Materials property statistics (measured or modeled)
  are needed to inform robust "performance QMU."

Thanks for Your Attention

From "Metallurgy of the RMS Titanic," NIST Internal Report 6118, by Tim Foecke:

Conclusions

• The steel used to construct the RMS Titanic's hull, though **adequate in strength**, possessed a **very low fracture toughness** at ice water temperatures

• The low toughness was likely due to a complex combination of factors, including **low Mn content**, a **low Mn/C ratio**, a **large ferrite grain size** and **large and coarse pearlite colonies**.

• There is evidently a **large variation in properties** among the 2000 plates that made up the hull of Titanic. This conclusion is based on the **very different microstructures** and fracture behavior observed in the two plate samples recovered to date. This is a **normal result of the variability of feedstock and rolling conditions** in turn-of-the-century ironworks.

...

• The microstructure of the rivets that evolved during their being driven into place, with the slag stringers oriented perpendicular to the tensile axis, may have been a direct contributor to the type and distribution of damage to the hull. This aspect is under further investigation.

• Given the knowledge base available to engineers at the time of the ship's construction, it is the author's opinion that **no apparent metallurgical mistakes were made** in the construction of the RMS Titanic.