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Collaborative damage mechanisms in high-purity Cu wires: an *in situ* XCT study

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Introduction

On the competition between Orowan Alternating Slip (OAS) and microvoid coalescence

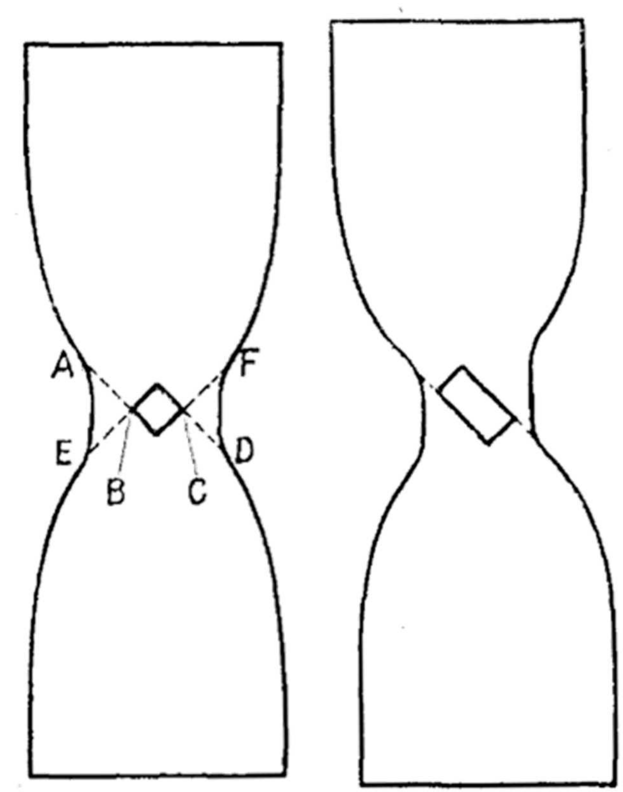
Orowan Alternating Slip (OAS)

OAS operates by conjugate slip at corners of a prismatic cavity

- Occurs in pure metals and some alloys

Outstanding questions:

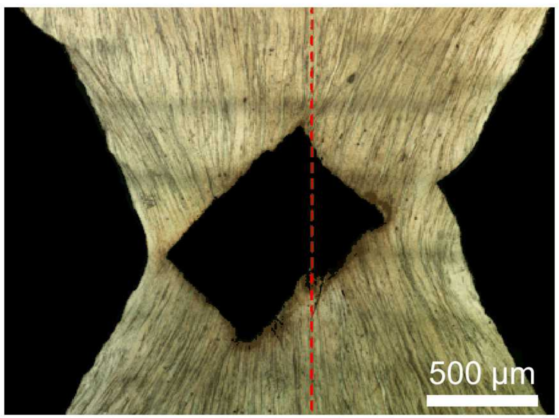
1. How does OAS initiate?
2. What is relationship / competition with other damage mechanisms?



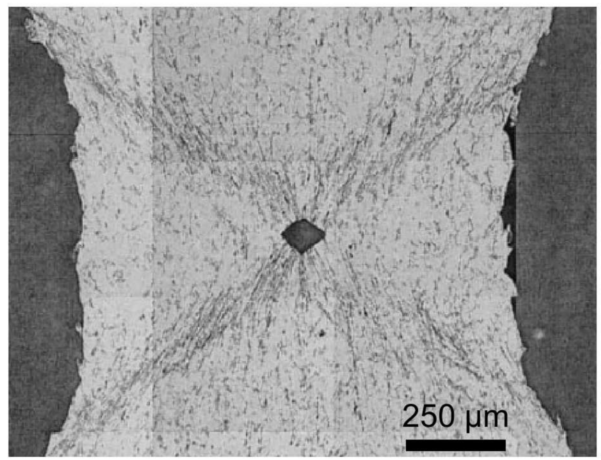
Orowan 1949

Orowan Alternating Slip (OAS)

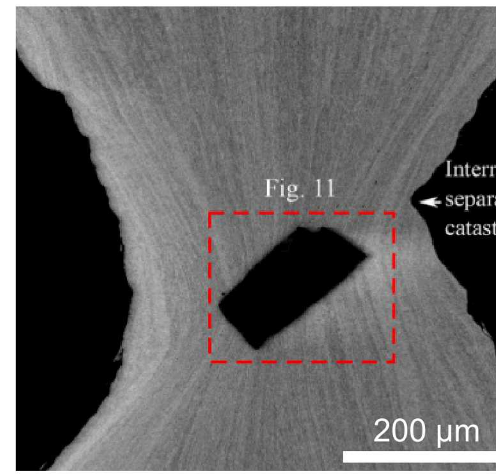
The only *interrupted in situ* experiments in the literature:



OFHC Copper (99.94%)
Ghahremaninezhad, *IJSS* 2011



Al 5754
Spencer, *Mat Sci Eng A* 2002

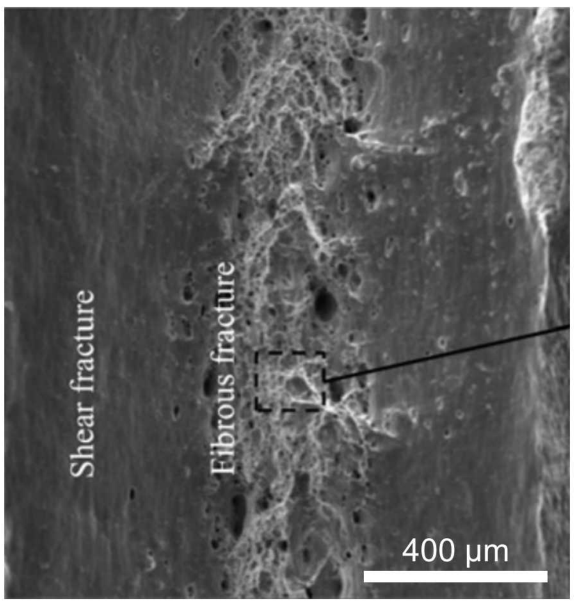


99.9% Ni (also 99.9% Cu)
Noell, *Acta Mat* 2018

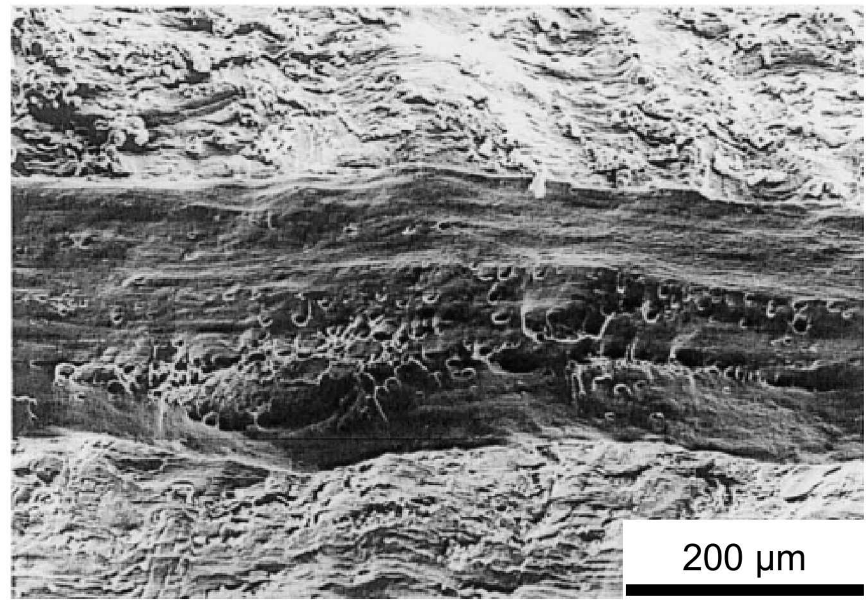
Ghahremaninezhad, *IJSS* 2011:
“A single cavity is nucleated at the center of the necked region” →
No microvoid nucleation / growth / coalescence!

Orowan Alternating Slip (OAS)

How to explain fracture surfaces?



OFHC Copper (99.94%)
Ghahremaninezhad, *IJSS* 2011

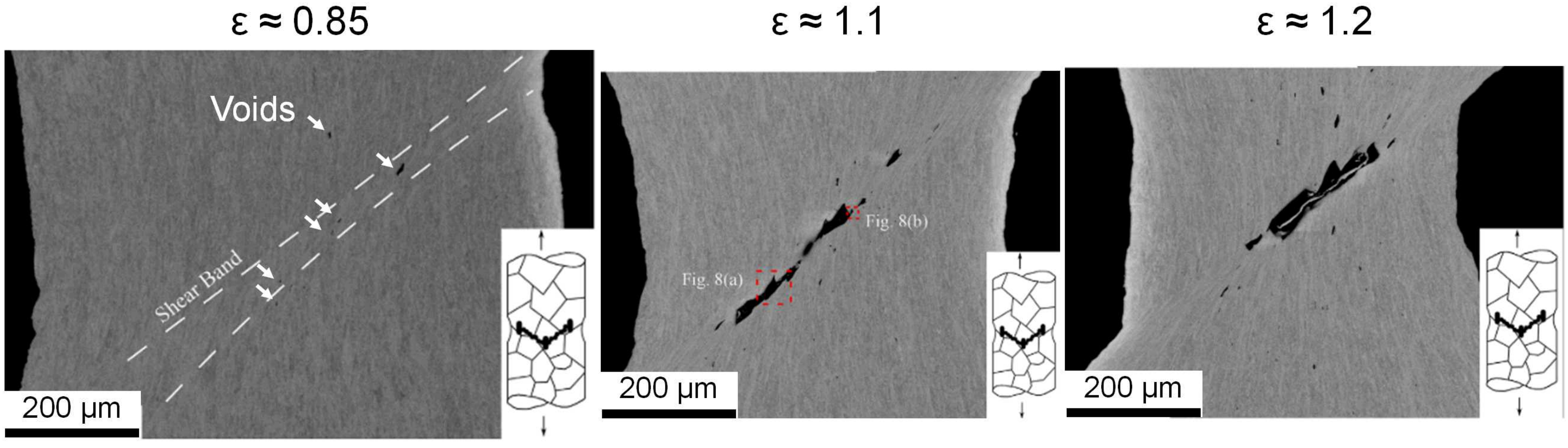


Al 5754
Spencer, *Mat Sci Eng A* 2002

Extensive coalescence / dimpled surface prior to transition to OAS

OAS vs. Void Coalescence

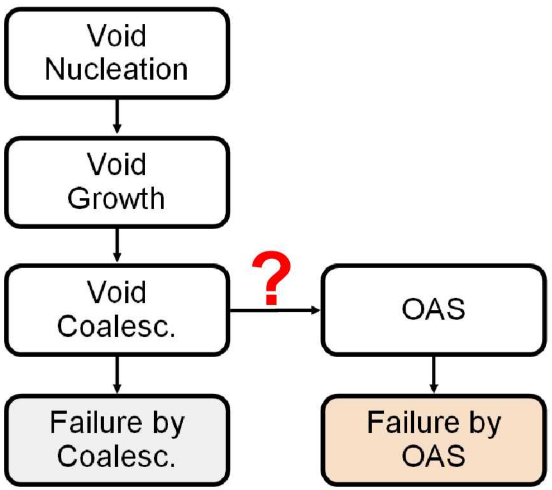
99.9% Cu (Noell *Acta Mat* 2018)



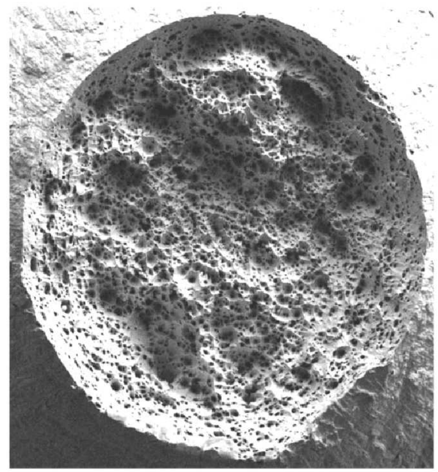
Detailed examination of the deformation process identifies activity of multiple damage mechanisms

OAS vs. Void Coalescence

What controls the transition from coalescence to OAS?



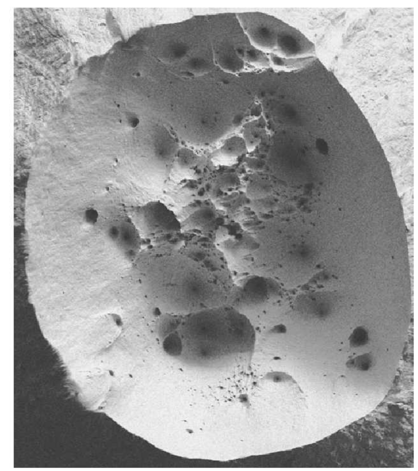
99.9% Cu



100 µm

Noell, Unpublished

99.999% Cu



100 µm

Noell, *Acta Mat* 2018

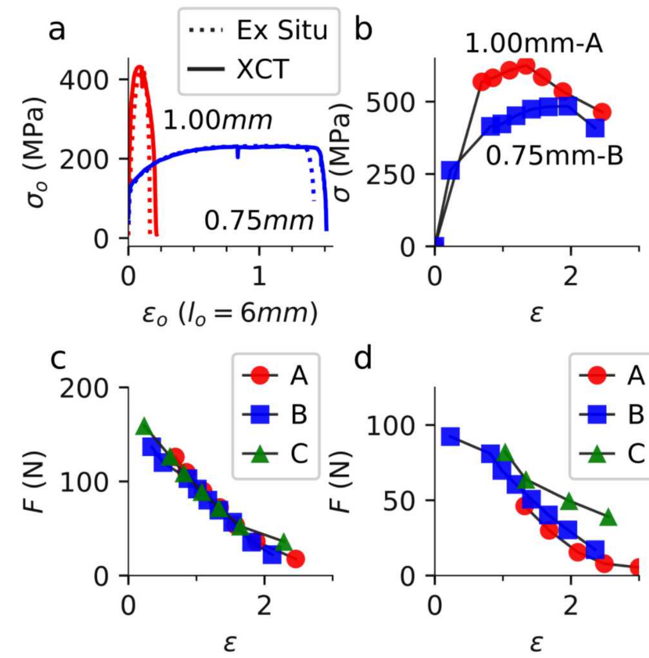
Damage mechanisms in Cu wires

In situ testing at Advanced Photon Source

Experiment overview

In situ testing performed at 2-BM at Advanced Photon Source

- 99.999% Cu wires
- 1 mm and 0.75 mm wire diameters
- Three tests on each size
- 3D tomograms with 0.65 μm voxel size



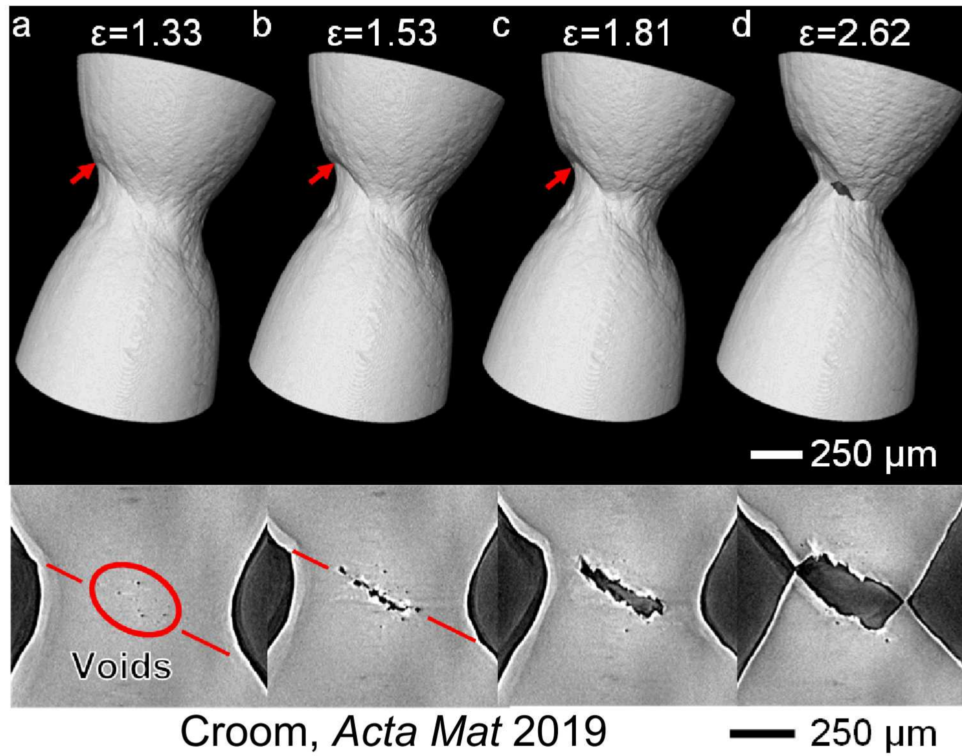
Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Complex sequence of events:

1. Shear band + Appearance of micron-sized voids
2. Coalescence
3. OAS growth of cavity

1 mm wires, 99.999% Cu



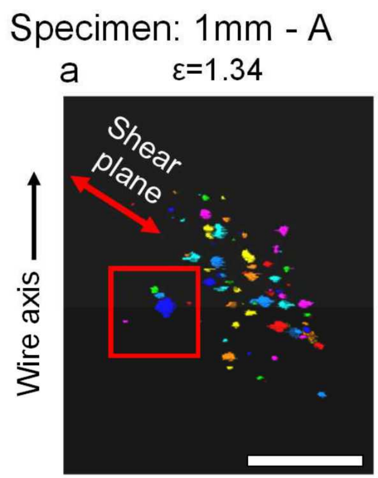
Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Key features:

1. Ellipsoidal cloud of voids

1 mm wires, 99.999% Cu



Scale bars: 125 μm

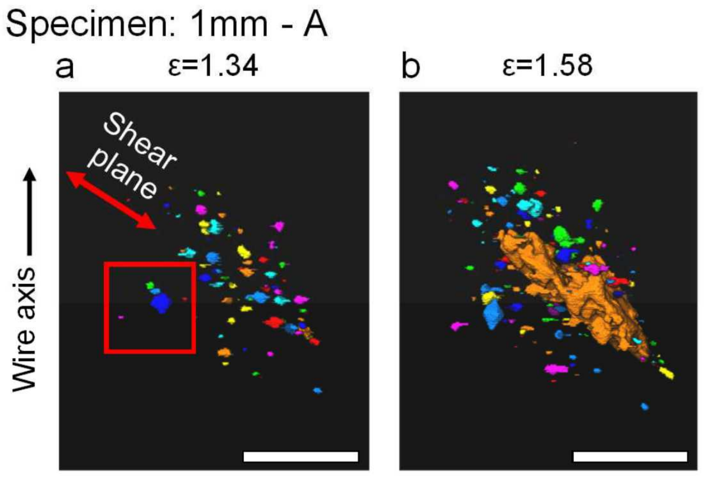
Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Key features:

1. Ellipsoidal cloud of voids
2. Coalescence along shear band
   - Consumes most voids on plane

1 mm wires, 99.999% Cu



Scale bars: 125 μm

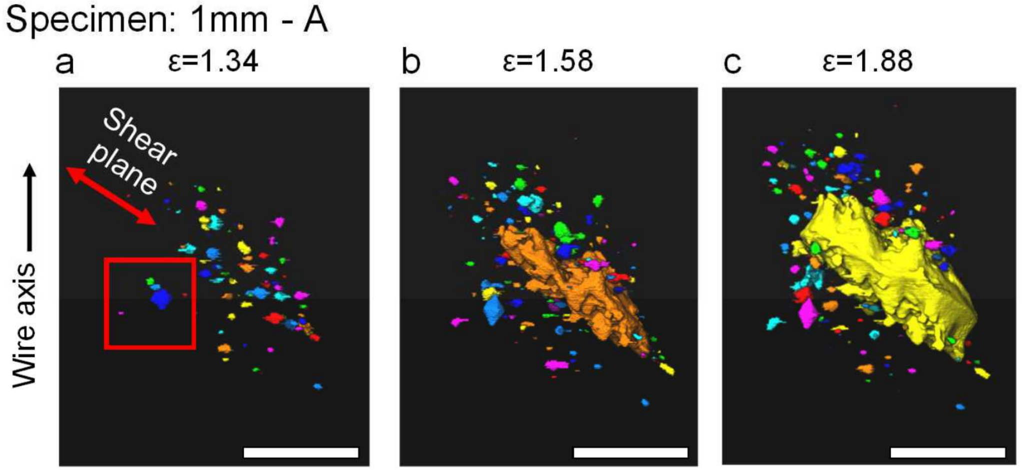
Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Key features:

1. Ellipsoidal cloud of voids
2. Coalescence along shear band
3. OAS growth of cavity

1 mm wires, 99.999% Cu



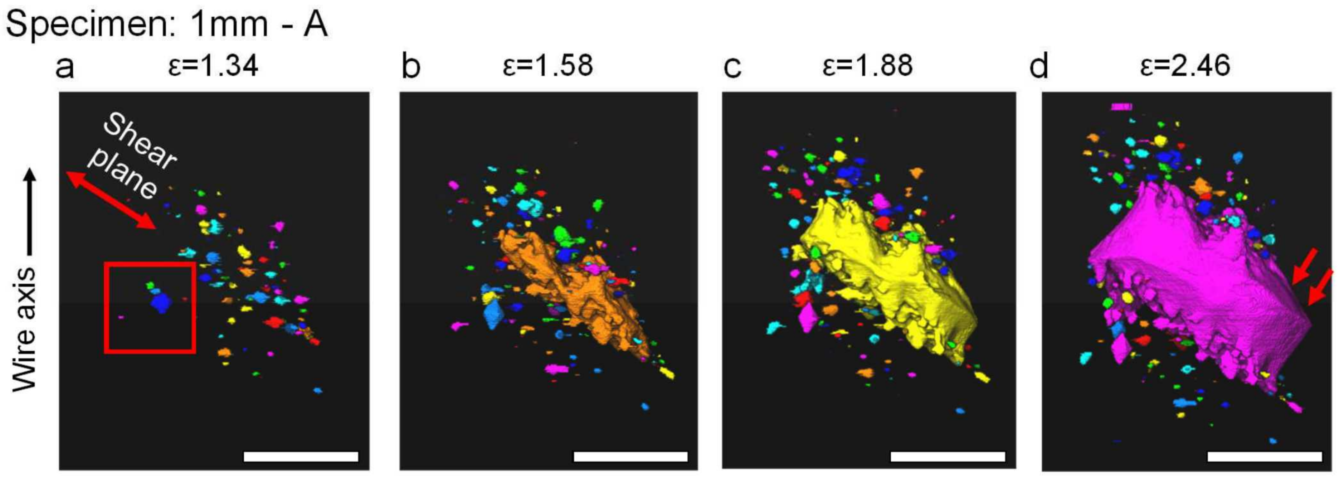
Scale bars: 125 µm

Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Key features:
1. Ellipsoidal cloud of voids
2. Coalescence along shear band
3. OAS growth of cavity
4. OAS growth until failure

1 mm wires, 99.999% Cu



Scale bars: 125 μm

Croom, *Acta Mat* 2019

Damage mechanisms in Cu

Key features:

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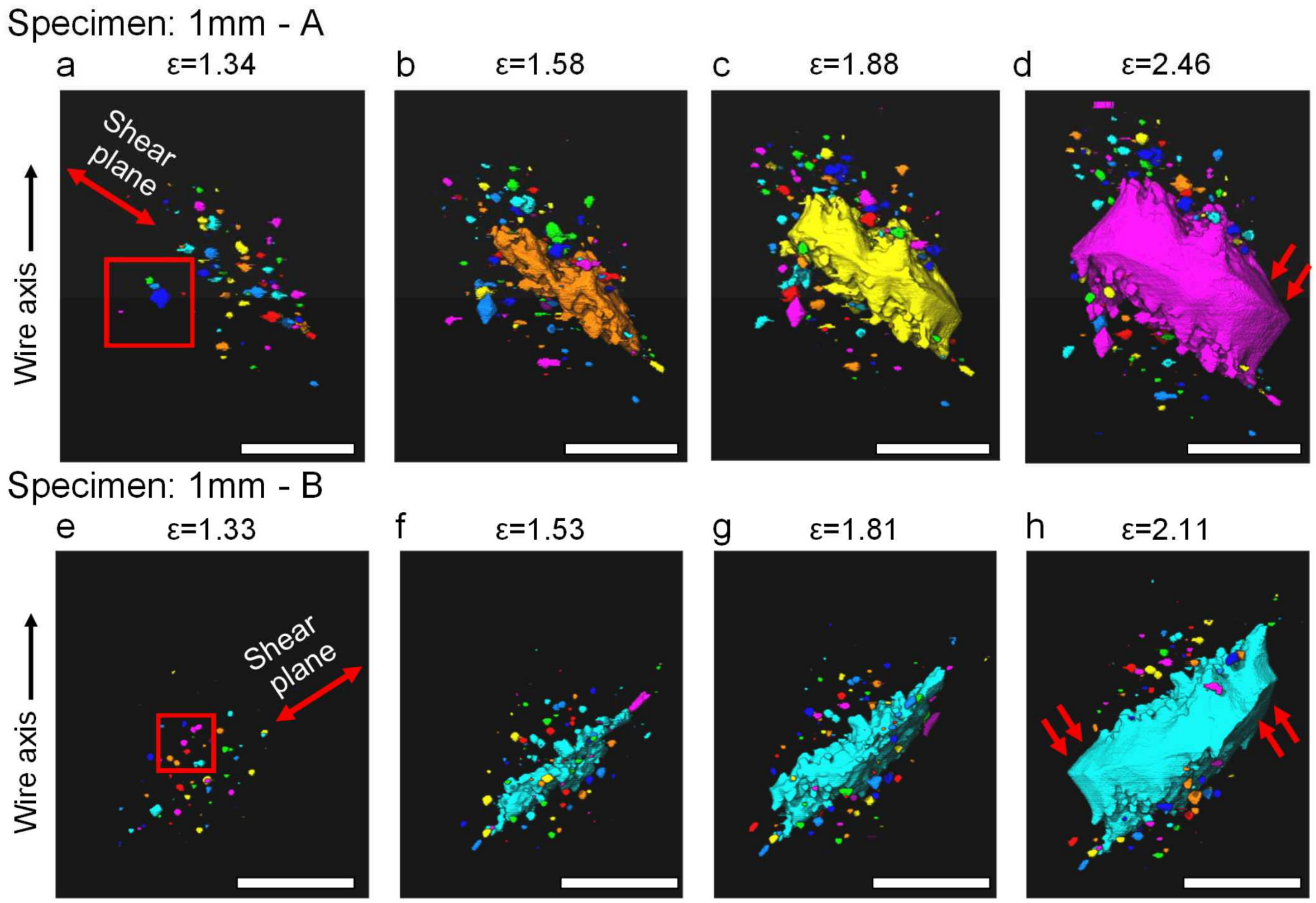
1 mm wires, 99.999% Cu

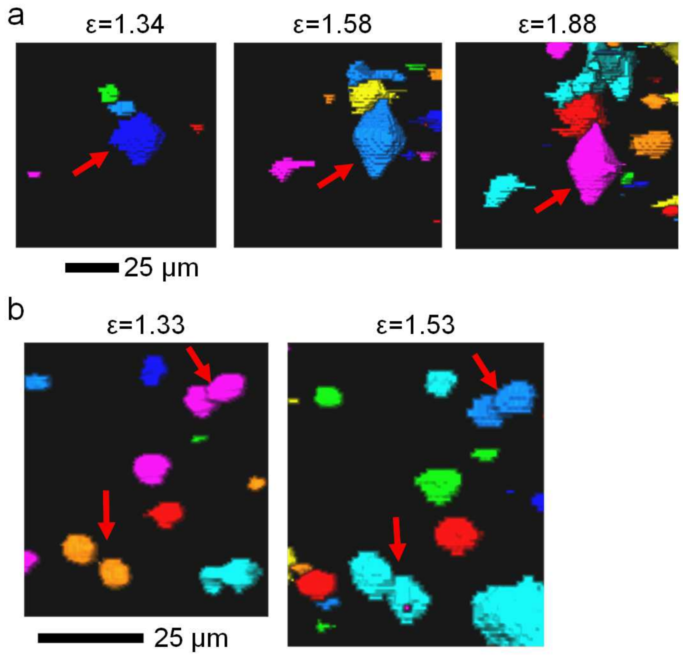


Scale bars: 125 μm

Damage mechanisms in Cu

Isolated instances of:
1. OAS growth
2. Void coalescence

Activation criterion of damage mechanism is local in nature



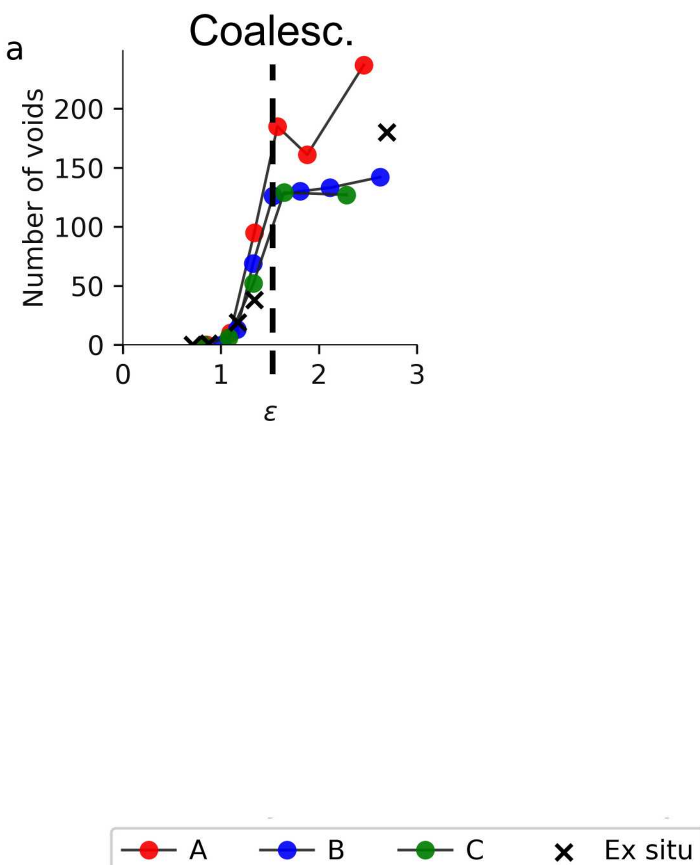
Croom, *Acta Mat* 2019

Damage kinetics

Quantitative analysis of void measurements

Void growth statistics

1 mm wires, 99.999% Cu

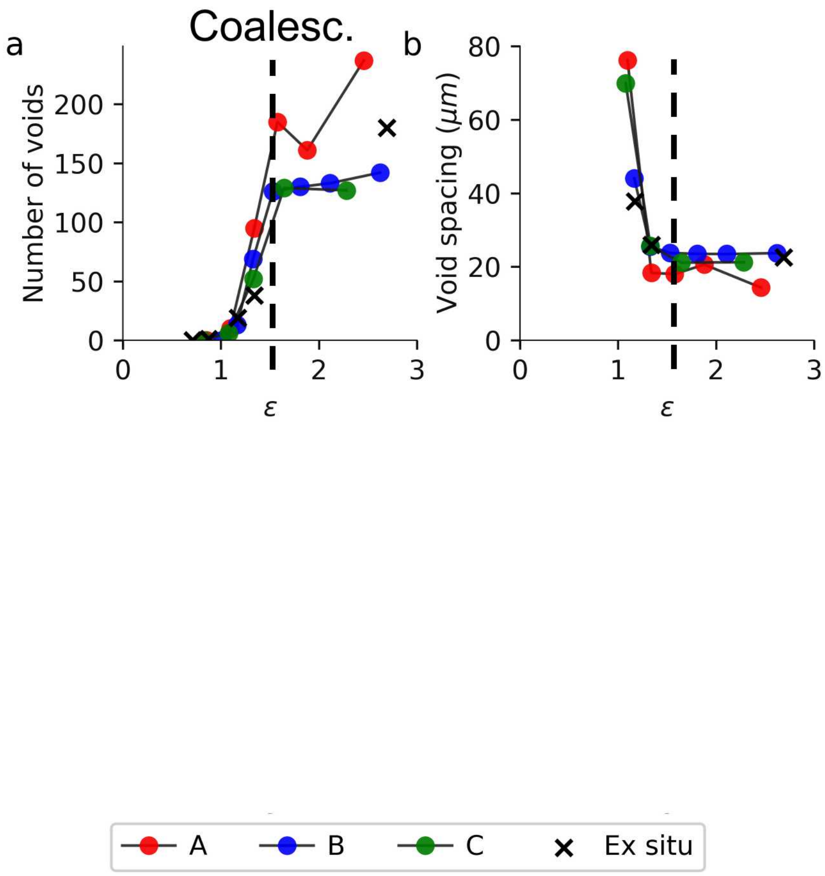


- Appearance of micron-sized voids:
  - Begins at $\varepsilon \approx 1$
  - Ends at $\varepsilon \approx 1.5$ (coalescence)

Croom, *Acta Mat* 2019

Void growth statistics

1 mm wires, 99.999% Cu

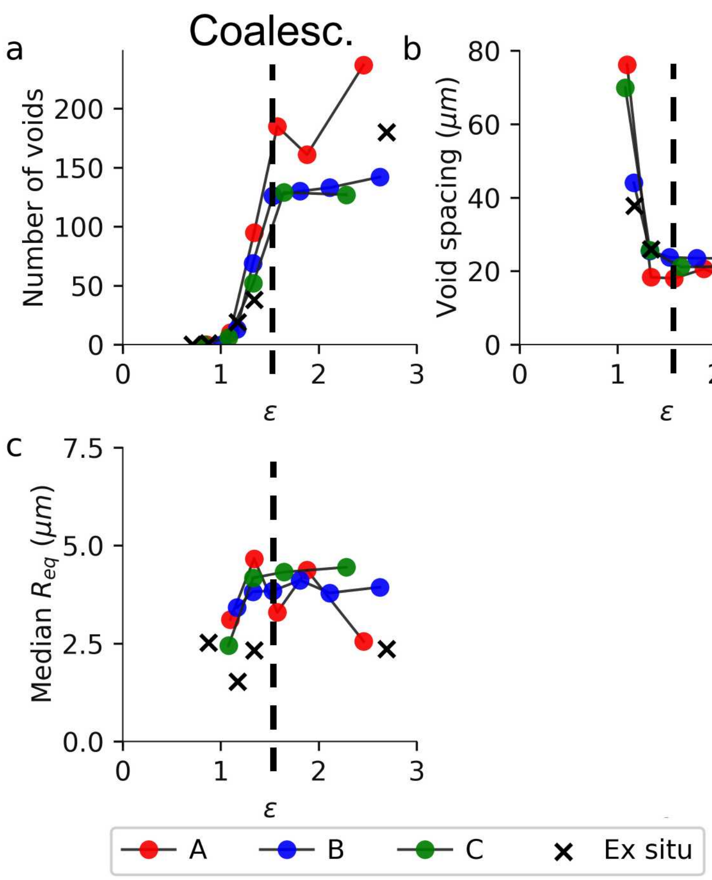


- Appearance of micron-sized voids:
  - Begins at $\varepsilon \approx 1$
  - Ends at $\varepsilon \approx 1.5$ (coalescence)
- Void spacing reaches minimum prior to coalescence

Croom, *Acta Mat* 2019

Void growth statistics

1 mm wires, 99.999% Cu

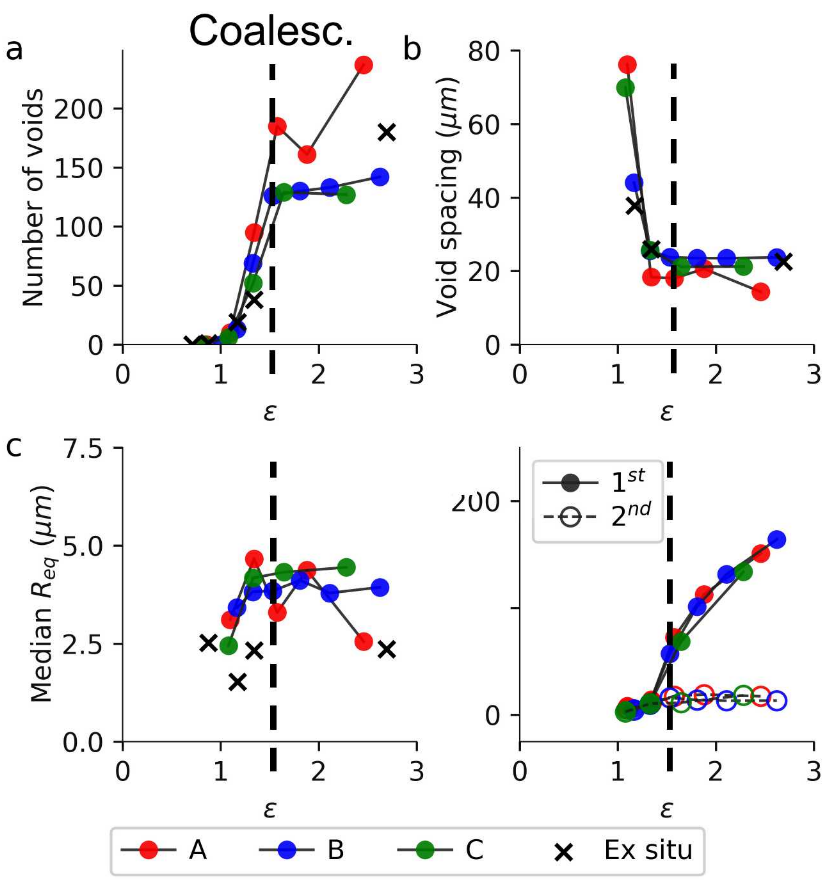


- Appearance of micron-sized voids:
  - Begins at $\varepsilon \approx 1$
  - Ends at $\varepsilon \approx 1.5$ (coalescence)
- Void spacing reaches minimum prior to coalescence
- Median void size plateaus at $\varepsilon \approx 1.25$

Croom, *Acta Mat* 2019

Void growth statistics

1 mm wires, 99.999% Cu

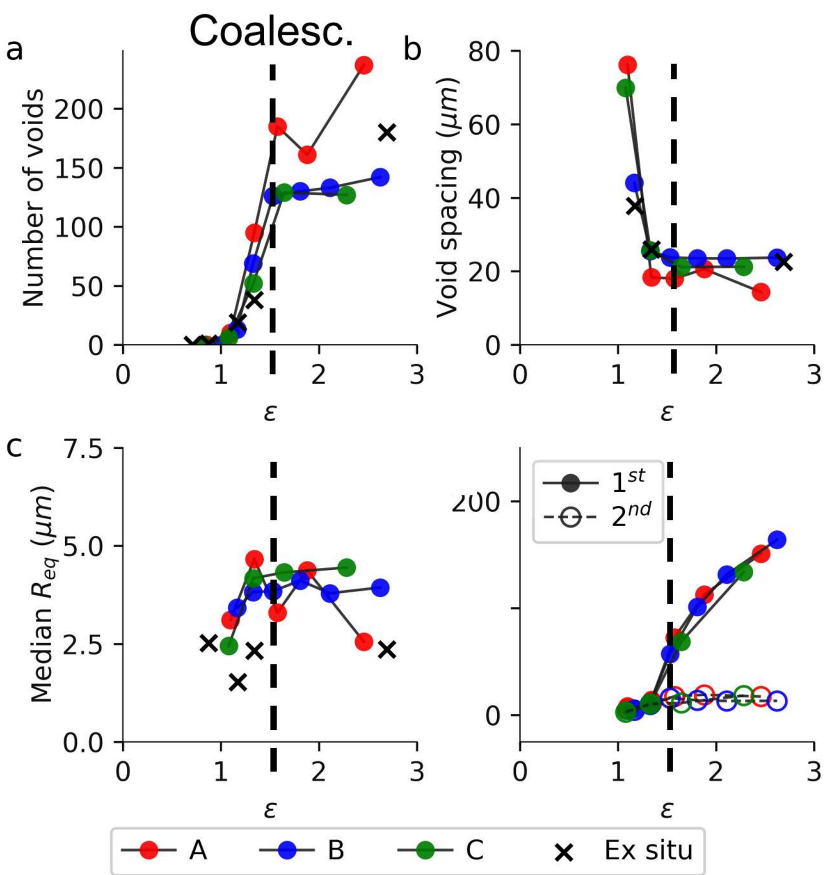


- Appearance of micron-sized voids:
  - Begins at $\varepsilon \approx 1$
  - Ends at $\varepsilon \approx 1.5$ (coalescence)
- Void spacing reaches minimum prior to coalescence
- Median void size plateaus at $\varepsilon \approx 1.25$
- Void growth restricted to OAS cavity $\varepsilon > 1.5$

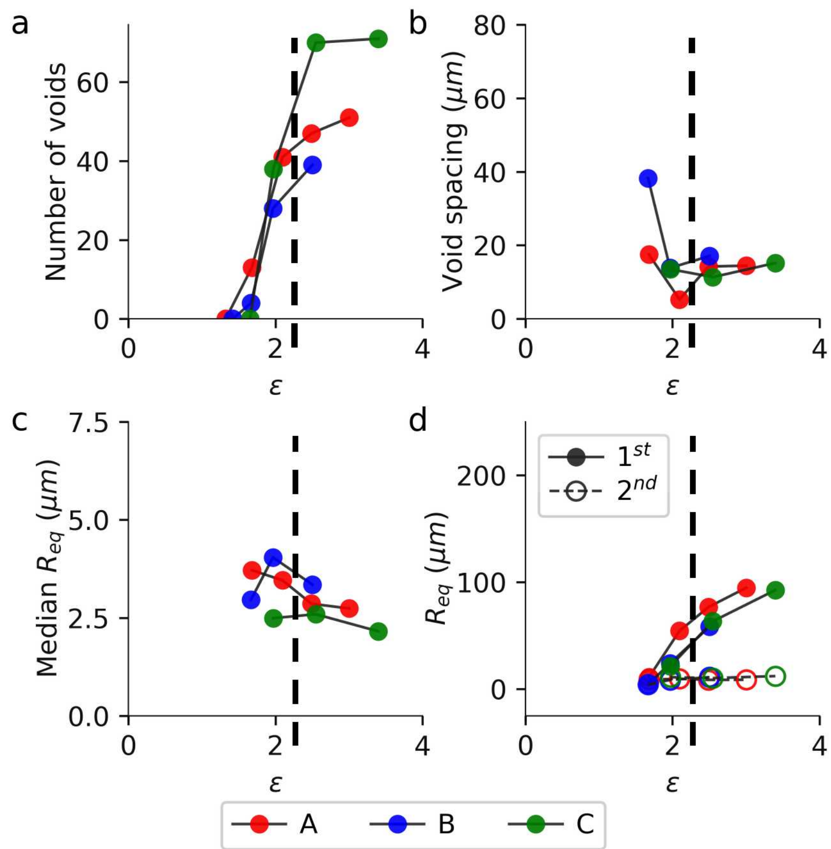
Croom, *Acta Mat* 2019

Void growth statistics

1 mm wires, 99.999% Cu



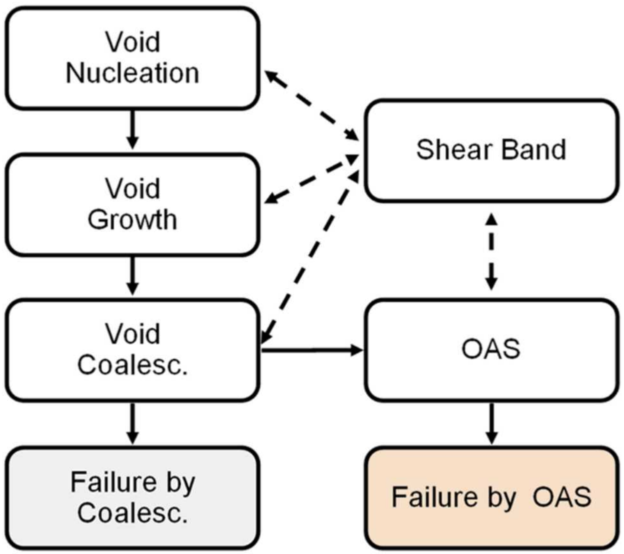
0.75 mm wires, 99.999% Cu

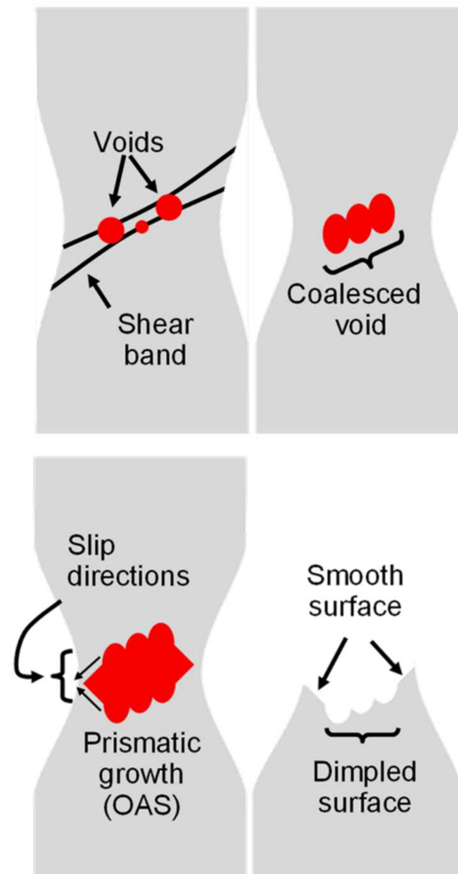


Croom, *Acta Mat* 2019

Conclusions

Summary of damage mechanisms





Conclusions

In situ XCT experiments reveal the *collaborative* nature of damage in high-purity Cu

- Failure involves sequence of damage mechanisms
- The activation of a new damage mechanism is:
  - Local in nature
  - Dependent on prior strain + damage history
- Modeling must account for collaboration between damage mechanisms