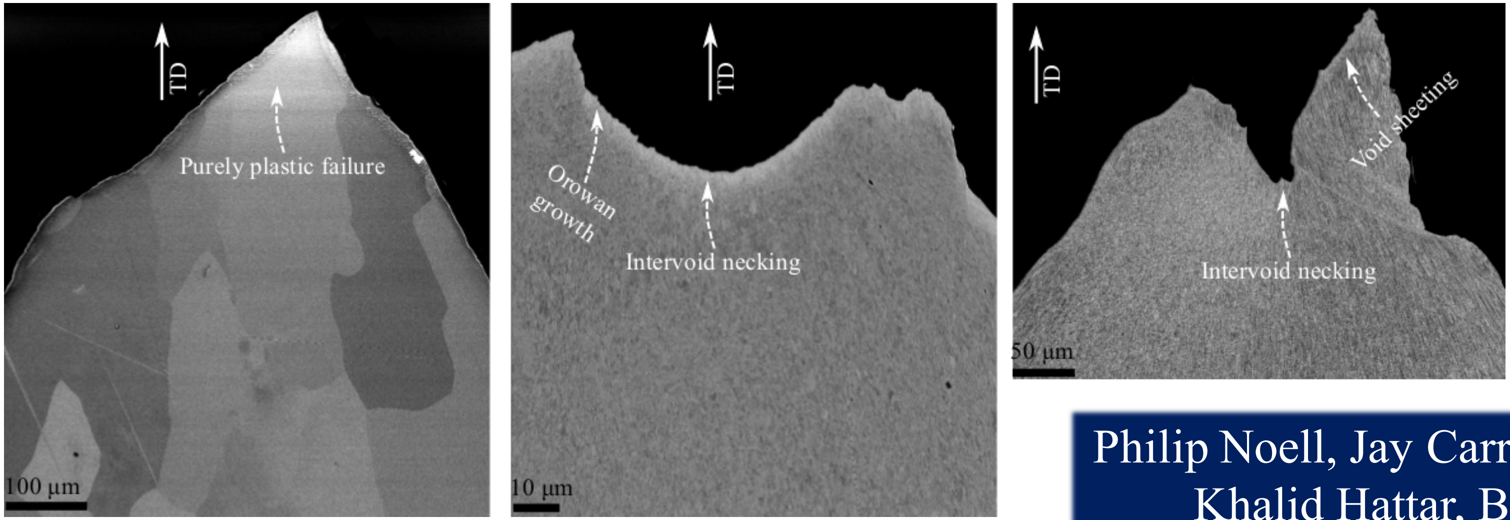
SAND2018-2431C

Void Initiation During Ductile Rupture of Pure Metals



Philip Noell, Jay Carroll, Brad Boyce, Khalid Hattar, Blythe Clark

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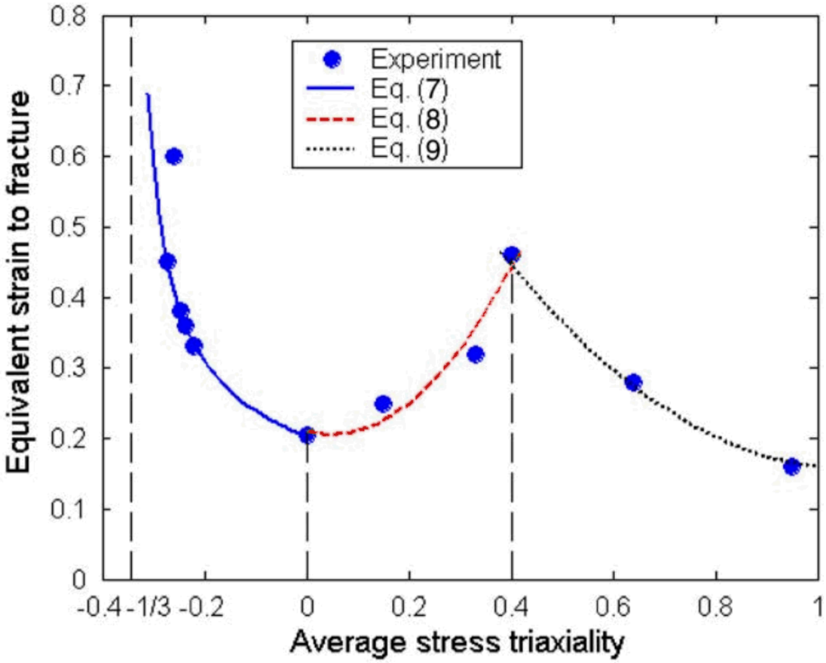
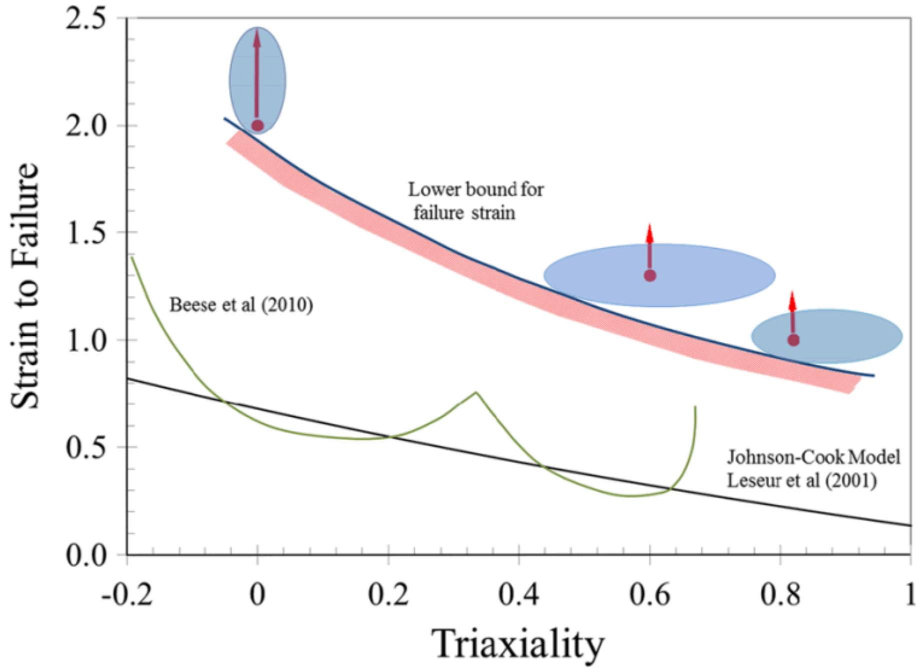
Predicting Strain to Failure



Bao, Yingbin, and Tomasz Wierzbicki. "On fracture locus in the equivalent strain and stress triaxiality space." *International Journal of Mechanical Sciences* 46.1 (2004): 81-98.



Ghahremaninezhad, A., and K. Ravi-Chandar. "Ductile failure behavior of polycrystalline Al 6061-T6 under shear dominant loading." *International Journal of Fracture* 180.1 (2013): 23-39.

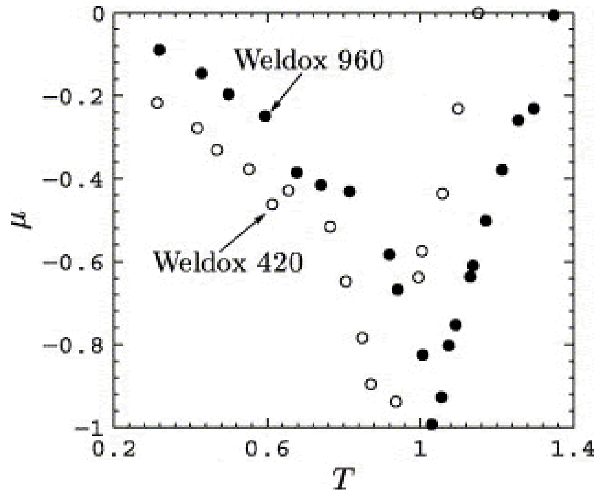
Several studies in the past two decades demonstrated that strain to failure decreases for stress triaxialities below ~1/3

So what are we to do with the results of Ravi-Chandar and coworkers? Does failure even happen under shear?

Proposed solutions: model the stress state more accurately and measure strain more accurately

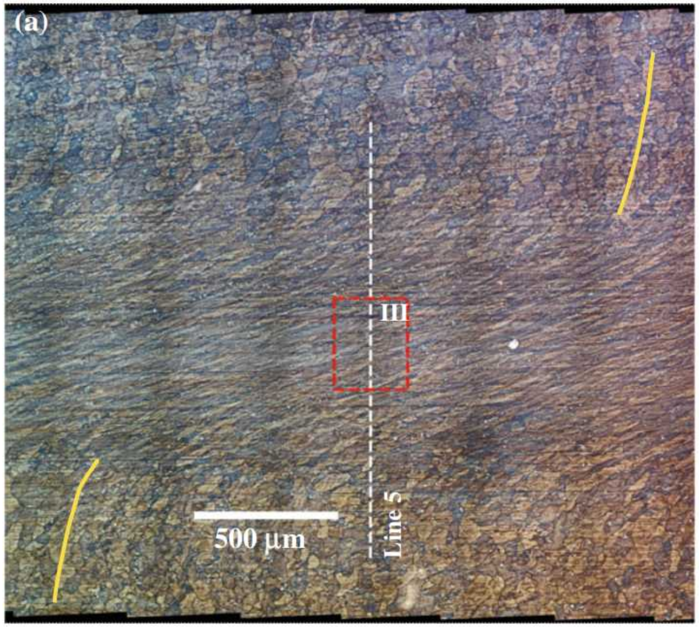
“Ductility [at low stress triaxialities] is strongly affected by the deviatoric stress state”

- Faleskog, Jonas, and Imad Barsoum. Tension–torsion fracture experiments Part I: Experiments and a procedure to evaluate the equivalent plastic strain." *International Journal of Solids and Structures* 50.25-26 (2013): 4241-4257.

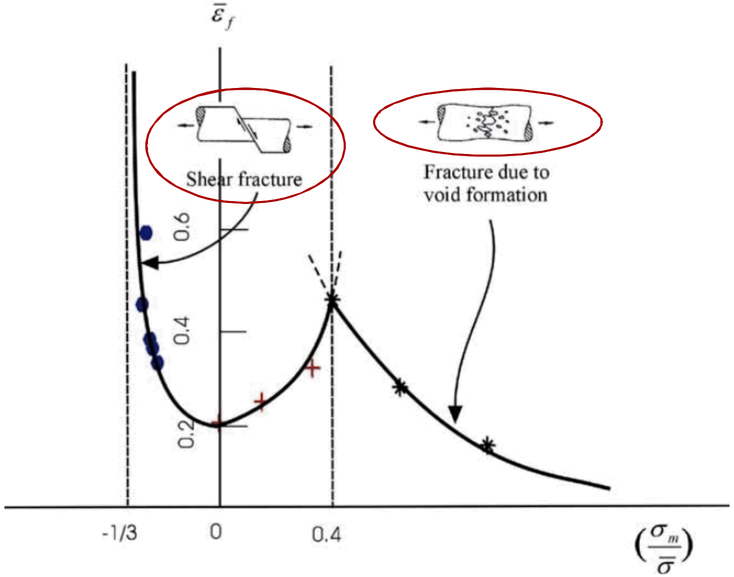


“The discrepancy between these models and our experimental results is attributed to … an inappropriately large gage length over which the strain is measured in conventional tests; in contrast, the present experimental results use a gage-length that is based on the characteristic microstructural length—the grain size.”

- Ghahremaninezhad, A., and K. Ravi-Chandar. "Ductile failure behavior of polycrystalline Al 6061-T6 under shear dominant loading." *International Journal of Fracture* 180.1 (2013): 23-39.

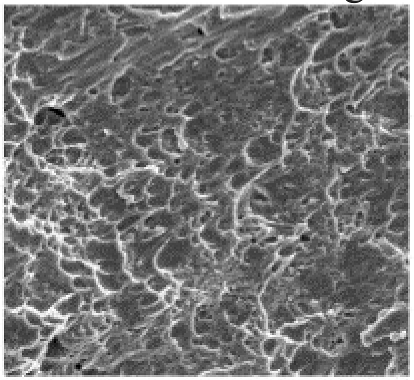


The strain to failure depends on the fracture mechanism, which is generally held to depend on the stress state

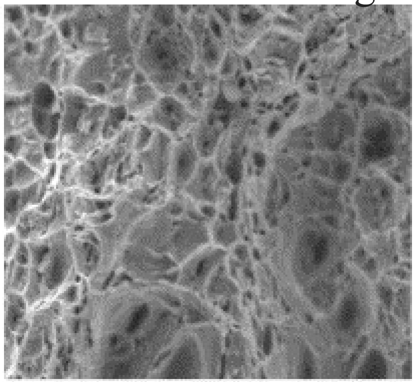


Bao, Yingbin, and Tomasz Wierzbicki. "On the cut-off value of negative triaxiality for fracture." *Engineering fracture mechanics* 72.7 (2005): 1049-1069.

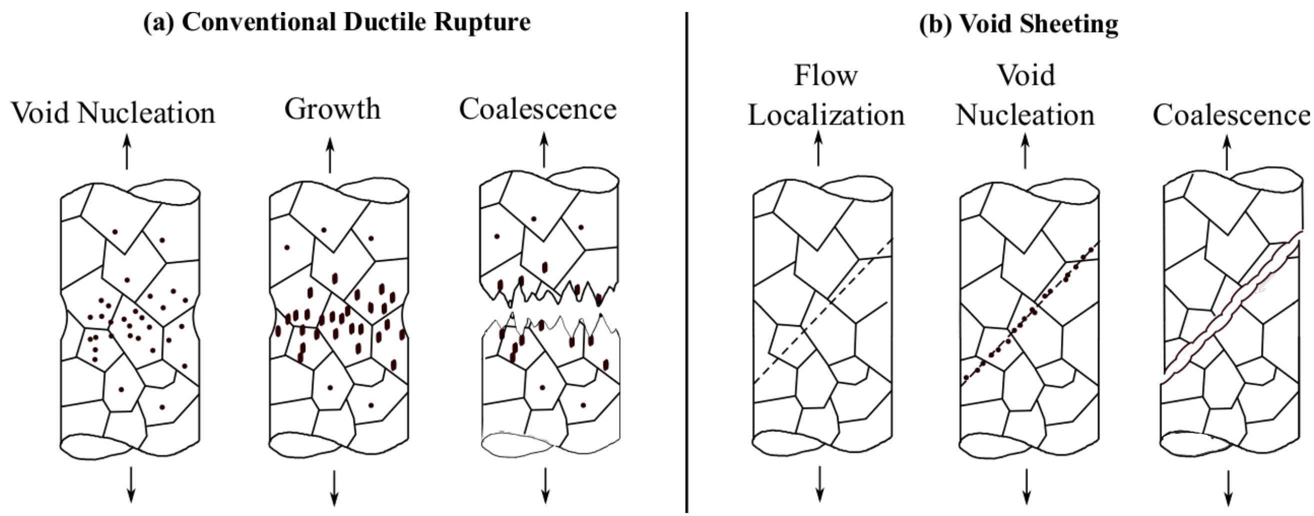
Failure under shear-dominated loading



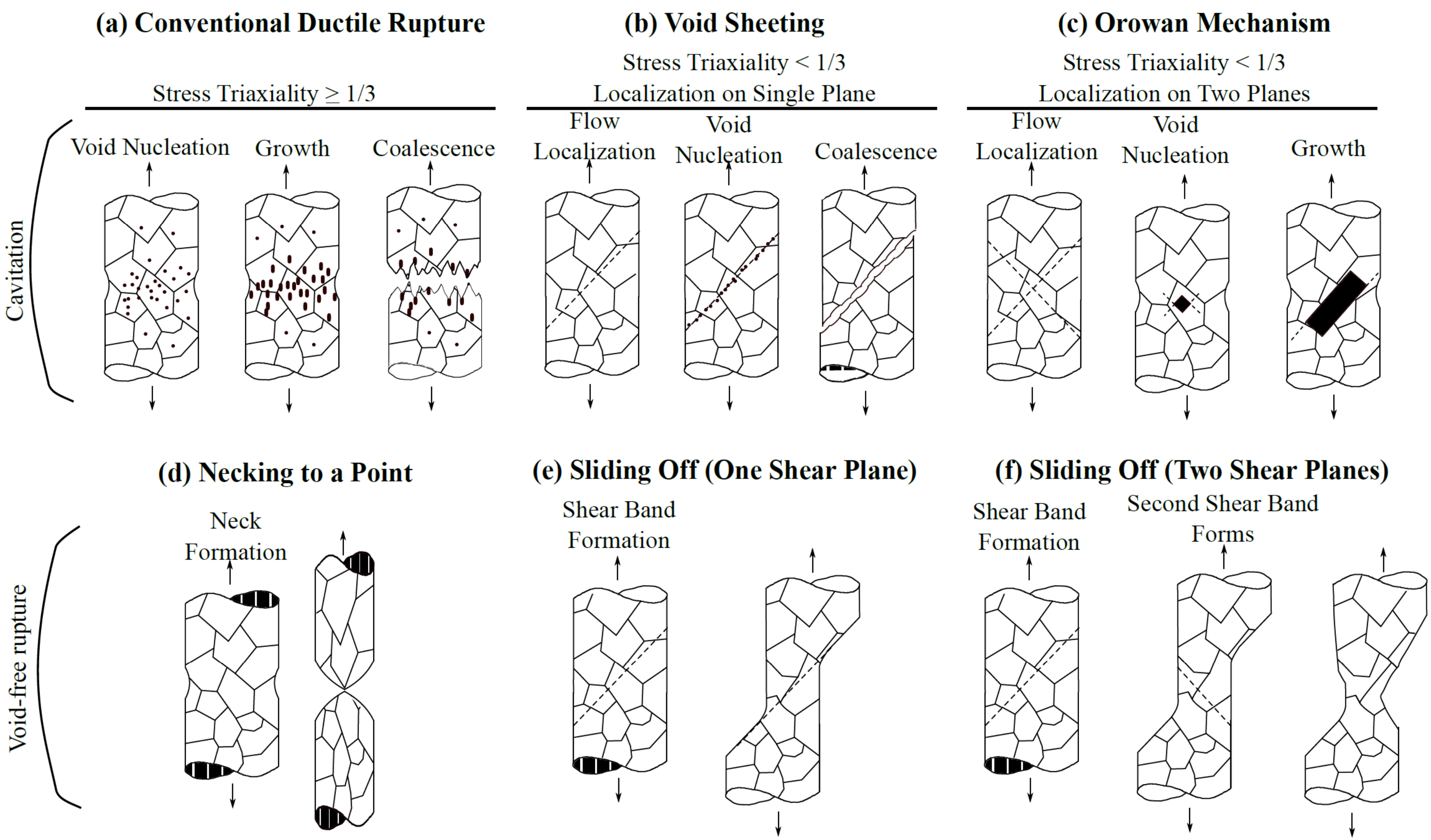
Failure under tensile-dominated loading



Barsoum, Imad, and Jonas Faleskog. "Rupture mechanisms in combined tension and shear—Experiments." *International Journal of Solids and Structures* 44.6 (2007): 1768-1786.

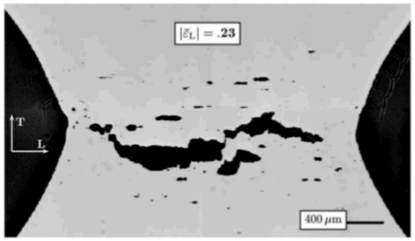


Failure Mechanisms

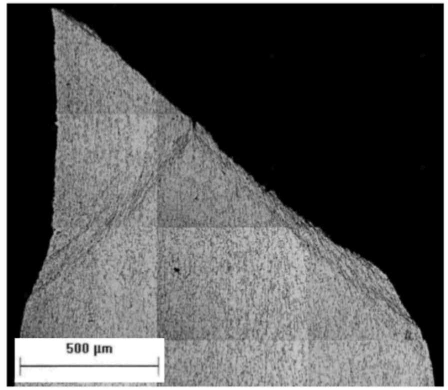


Cavitation

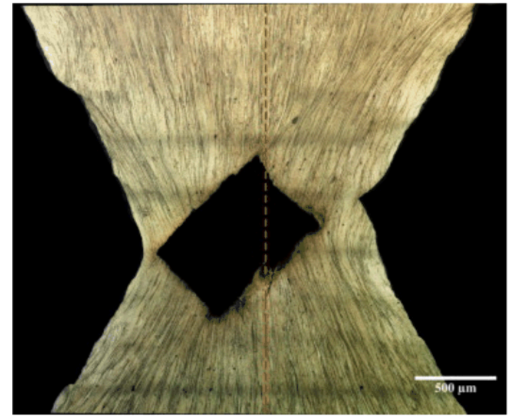
(a) Conventional Ductile Rupture



(b) Void Sheeting

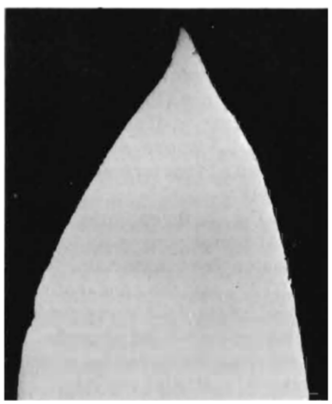


(c) Orowan Mechanism

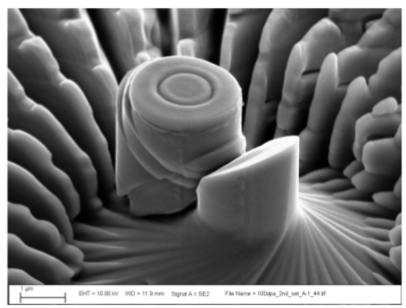


Void-free rupture

(d) Necking to a Point

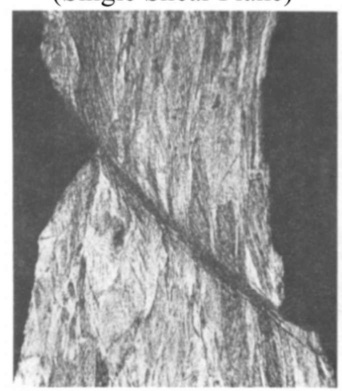


(e) Sliding Off (One Shear Plane)

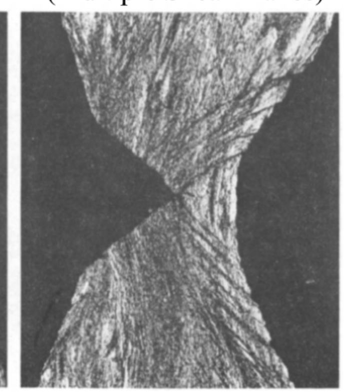


(f) Sliding Off (Two Shear Planes)

Early Stage (Single Shear Plane)



Late Stage (Multiple Shear Planes)



G. Y. Chin, W. Hosford, and W. Backofen, “Ductile fracture of aluminum,” Transactions of the Metallurgical Society of AIME, vol. 230, no. 3, p. 437, 1964.

A. Ghahremaninezhad and K. Ravi-Chandar, “Ductile failure in polycrystalline ofhc copper,” International Journal of Solids and Structures, vol. 48, no. 24, pp. 3299–3311, 2011.

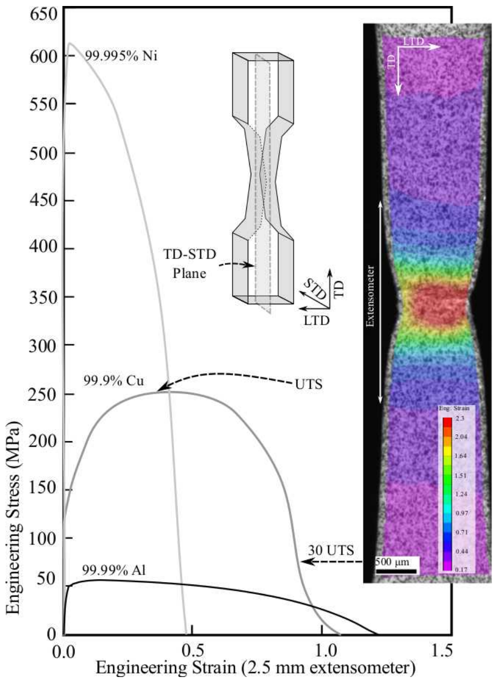
J. Sharon, K. Hattar, B. Boyce, and L. Brewer, “Compressive properties of< 110> cu micropillars after high-dose self-ion irradiation,” Materials Research Letters, vol. 2, no. 2, pp. 57–62, 2014.

A. Benzerga, J. Besson, and A. Pineau, “Anisotropic ductile fracture: Part i: experiments,” Acta Materialia, vol. 52, no. 15, pp. 4623–4638, 2004.

K. Spencer, S. Corbin, and D. Lloyd, “The influence of iron content on the plane strain fracture behaviour of aa 5754 al–mg sheet alloys,” Materials Science and Engineering: A, vol. 325, no. 1, pp. 394–404, 2002.

I. E. French and P. F. Weinrich, “The influence of hydrostatic pressure on the tensile deformation and fracture of copper,” Metallurgical and Materials Transactions A, vol. 6, no. 4, pp. 785–790, 1975.

Hypothesis: the active failure mechanism also depends on void nucleation

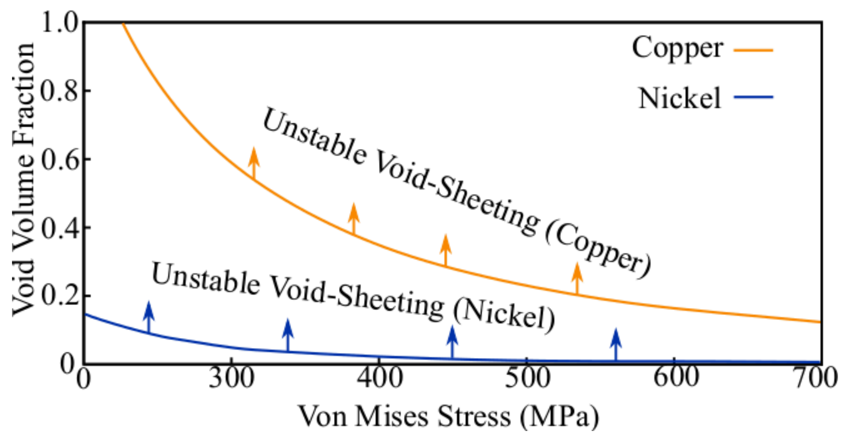


$$m\left(\frac{A}{\bar{\sigma}}\right)^{1/m} = VN_v$$

Tierlinck *et al.* proposed that void sheeting occurs when work hardening within the shear band cannot compensate for the increased shear stress associated with a loading increment.

Teirlinck, D., et al. "Fracture mechanism maps in stress space." *Acta Metallurgica* 36.5 (1988): 1213-1228.

m, A – work hardening exponents
σ – the von Mises stress
V – the volume of a void
N_v – the density of spherical voids per unit volume

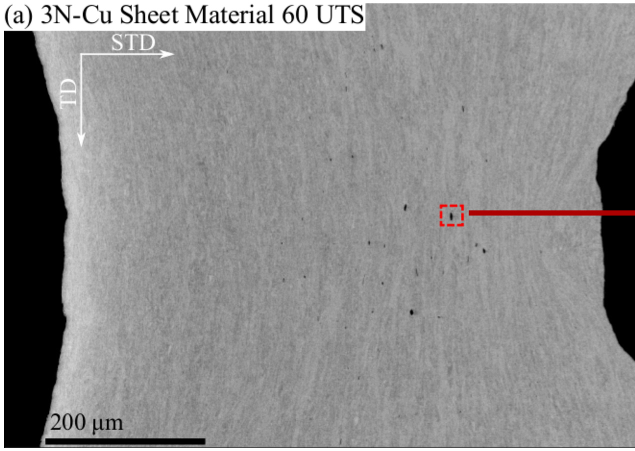


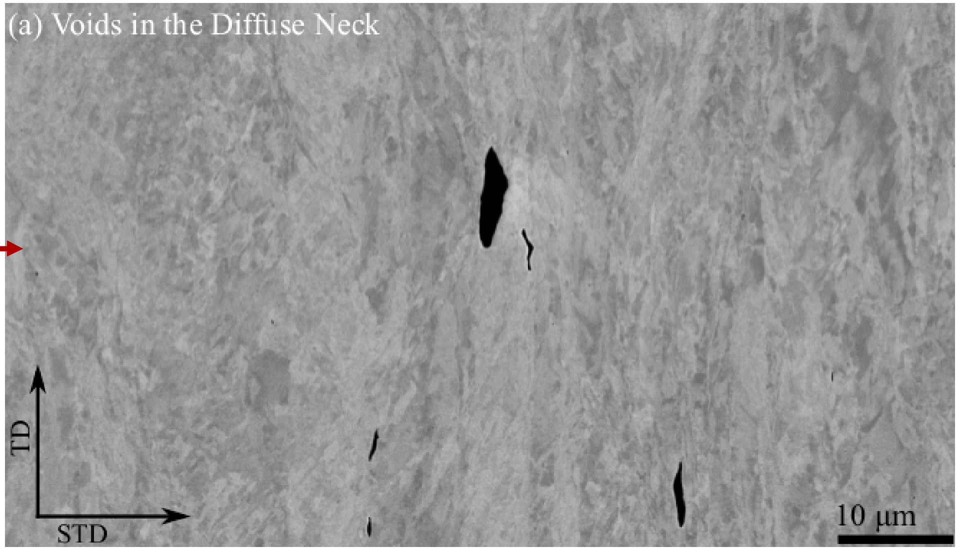
Specimen	Dominant Rupture Mechanisms	Stress Triaxiality (σ_{tr})
4N-Al Sheet	Necking to a Point	High
5N-Al Sheet	N+G+C	High
5N-Cu Wire	N+G+C→Void Sheeting→Orowan Mech.	High→Low→Low
3N-Cu Sheet	N+G+C→Void Sheeting→Orowan Mech.	High→Low→Low
4N-Ni Wire	N+G+C→Void Sheeting	High→Low
4N-Ni Sheet	Sliding Off→Void Sheeting→Orowan Mech.	High→Low→Low

Series of interrupted tensile tests were performed on high-purity copper, nickel, and aluminum materials

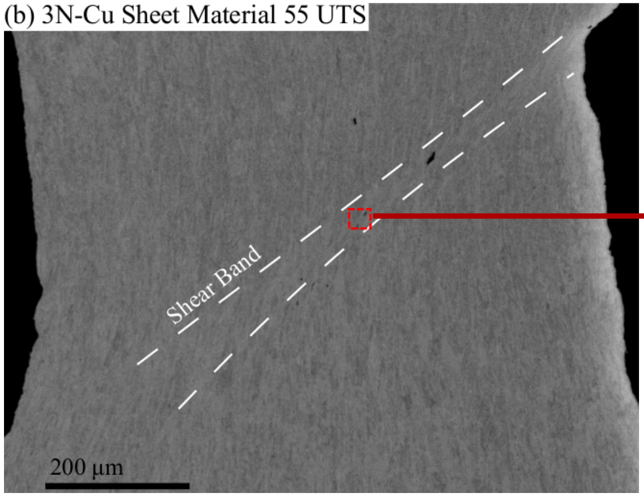
These demonstrated the relationship between failure mechanism and void nucleation

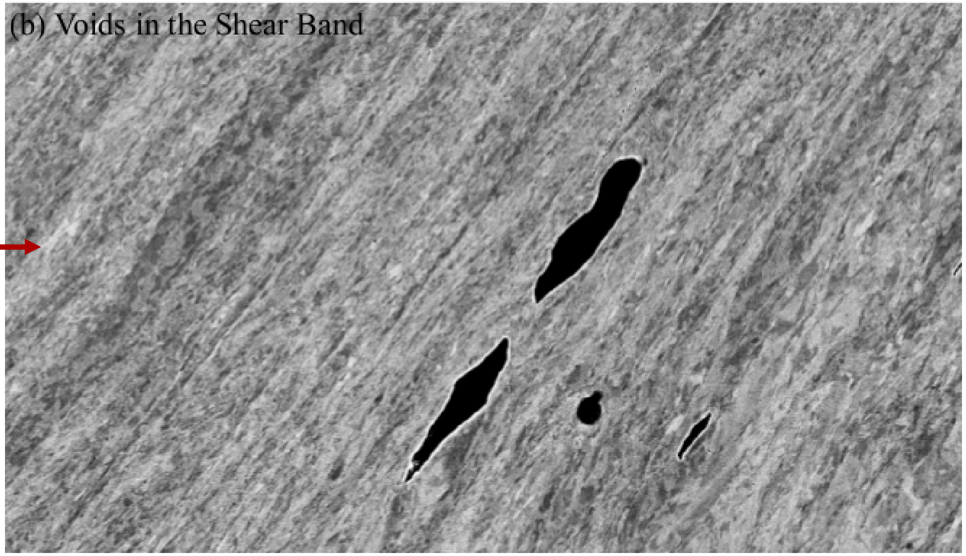
Fracture in High-Purity Copper: Void Nucleation





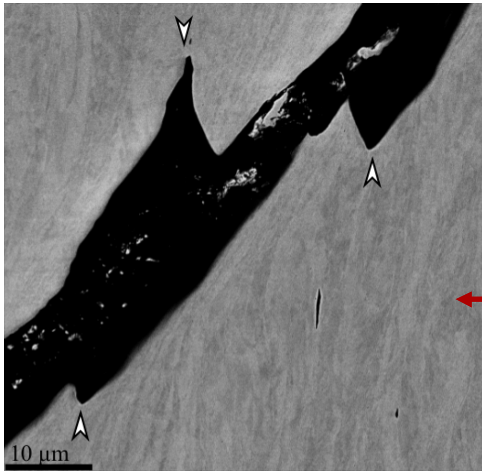
Initially, voids nucleate throughout the diffuse neck

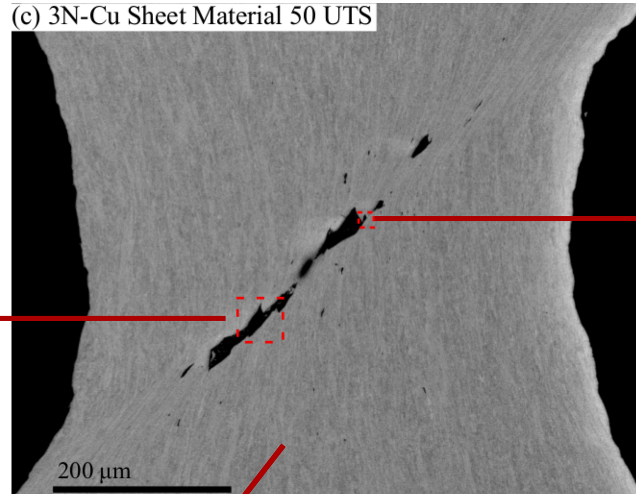


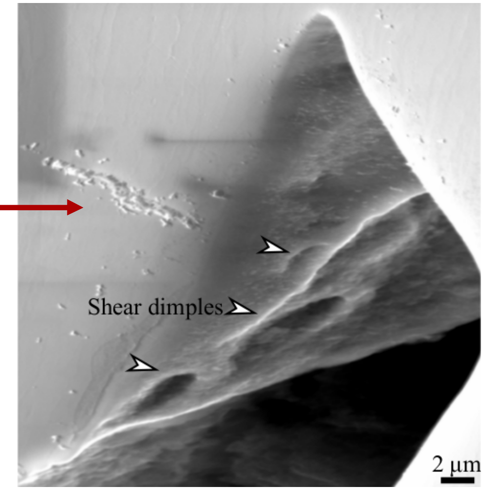


Eventually strain localizes in a shear band.
Preexisting voids are elongated along the shear axis and new voids nucleate within the shear band

Fracture in High-Purity Copper: Cavity Formation

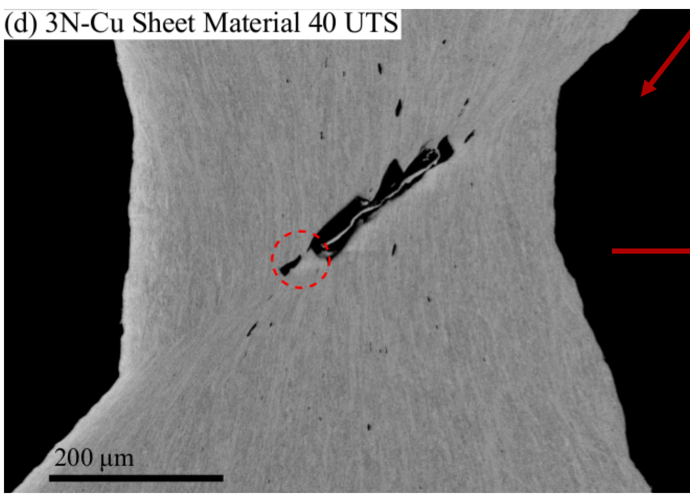


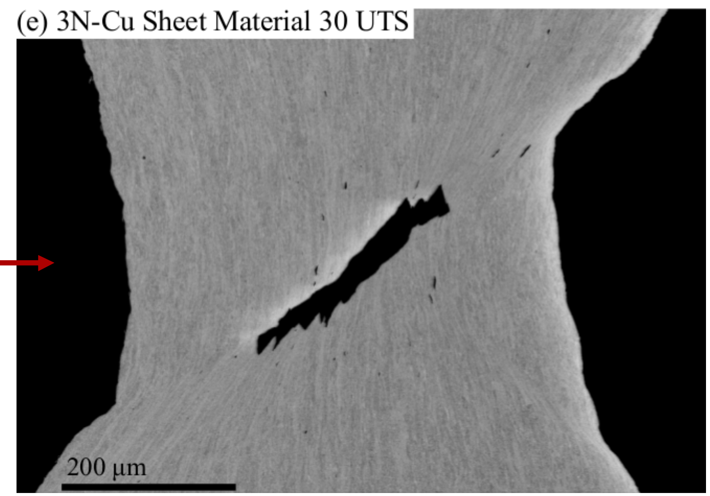




Preexisting voids in the shear band coalesce

Microscale void-sheeting is an important coalescence mechanism

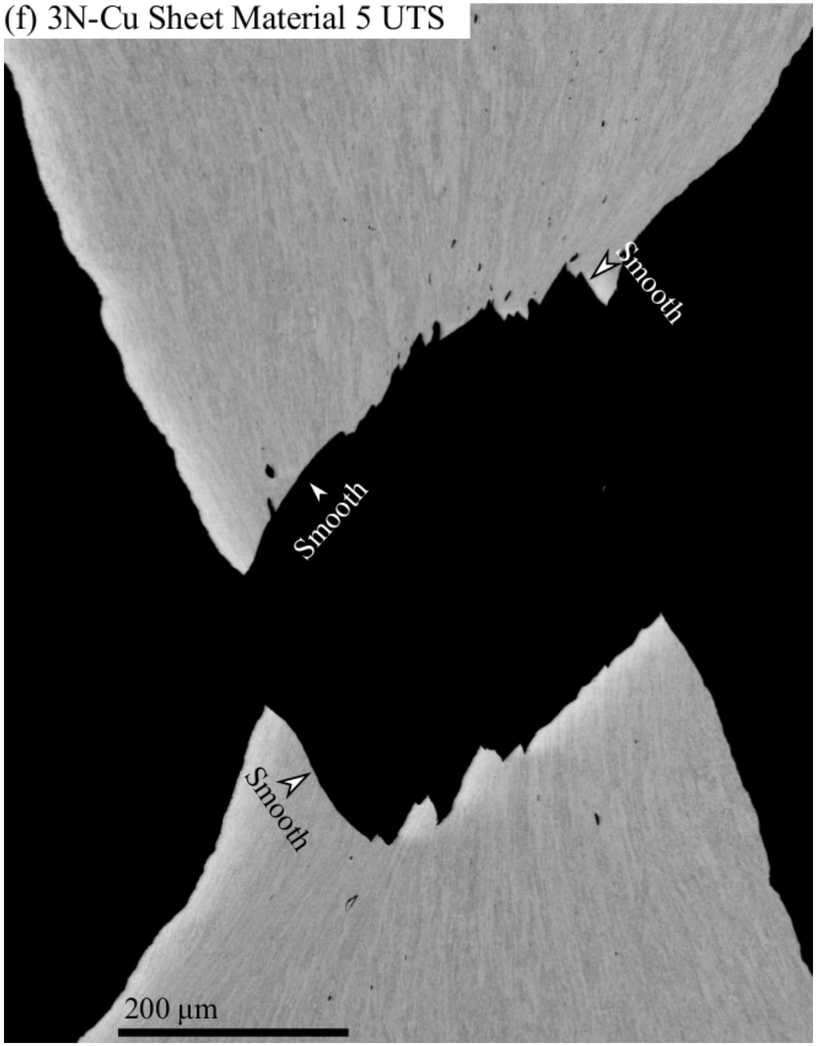




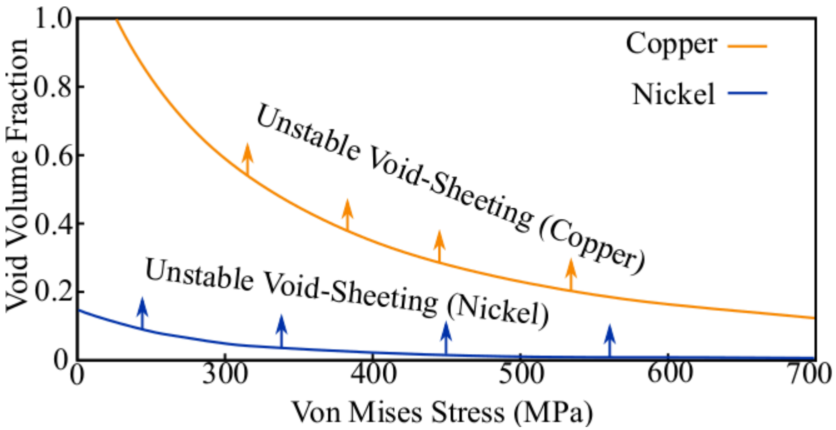
Eventually, a central, prismatic cavity forms

It continues to grow by coalescing with preexisting voids

Fracture in High-Purity Copper: Final Failure

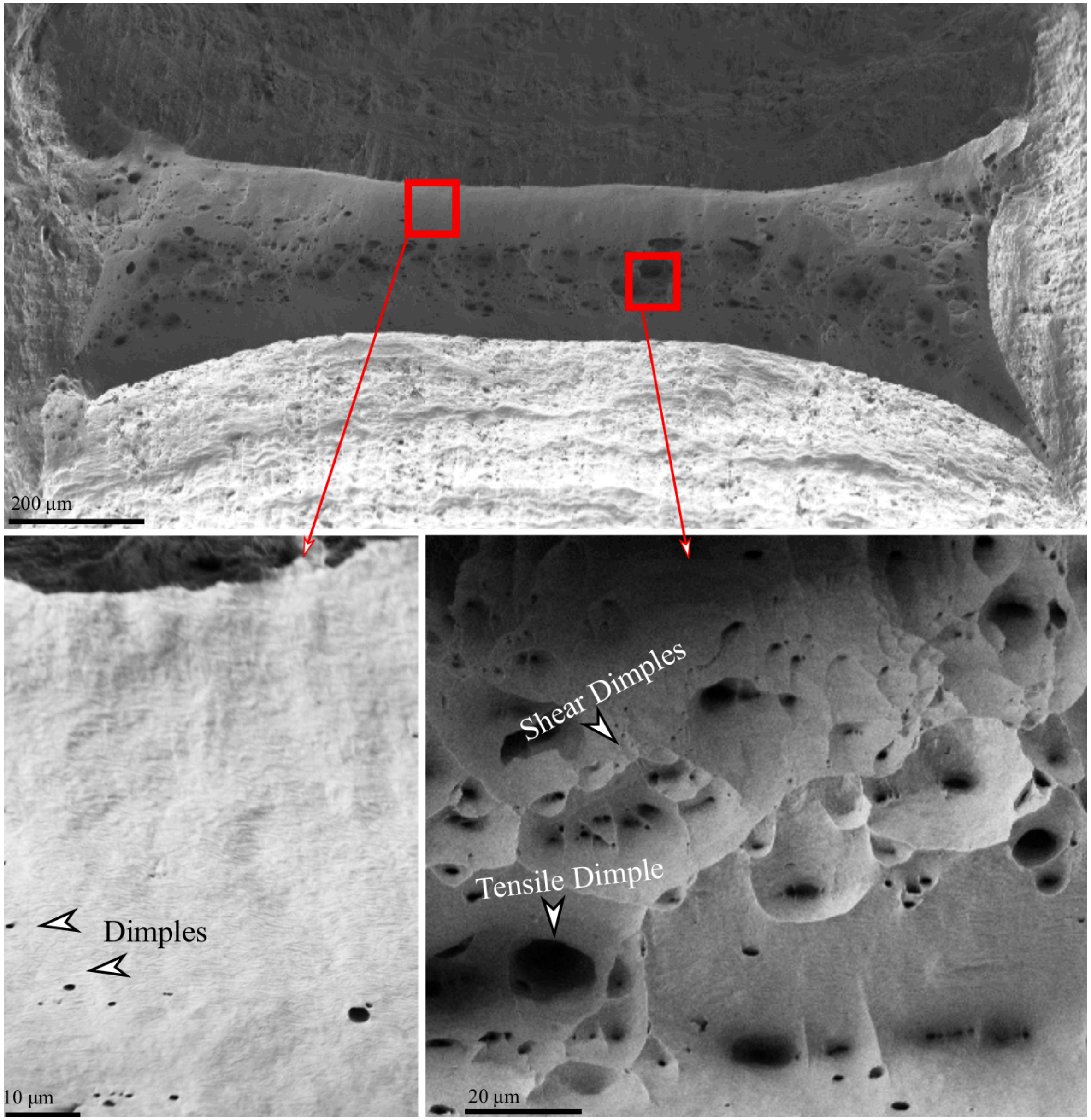


As the cavity grows into areas where there are few or no preexisting voids, the Orowan mechanism of growth begins to dominate. Final fracture is controlled by this mechanism



Copper is predicted to be relatively resistant to rupture by "uncontrolled" void sheeting. Since the void volume fraction decreases away from the center, the relative importance of void sheeting also decreases…

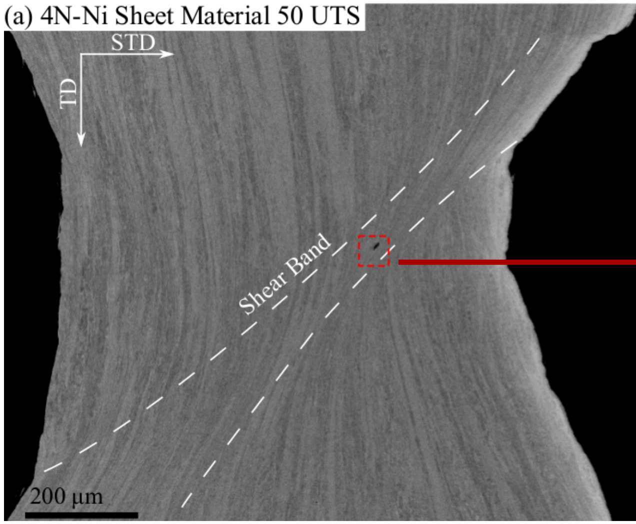
Copper Fracture Surface

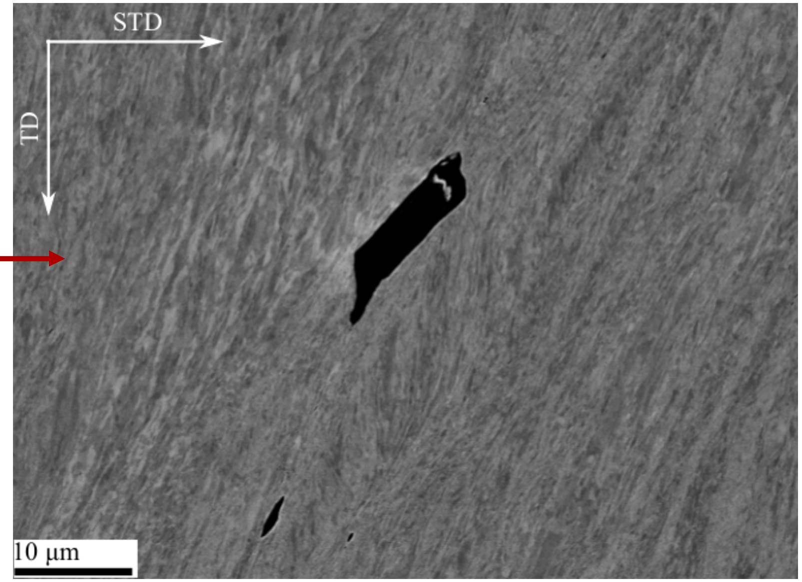


The fracture surface of a high-purity copper specimen is shown. Evidence of three failure mechanisms can be seen.

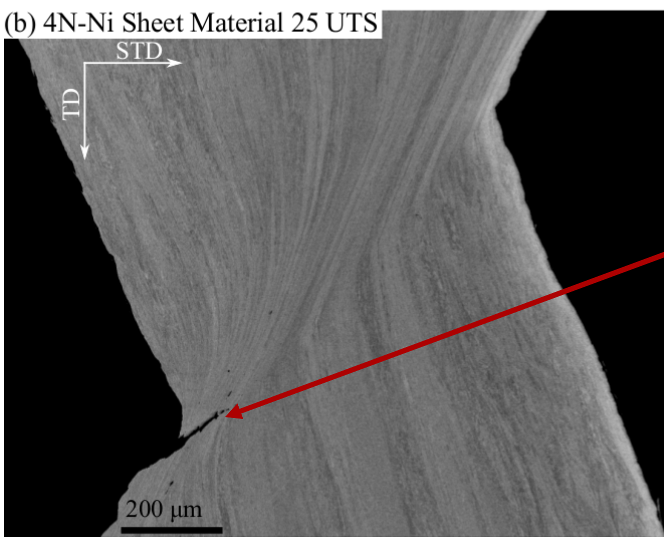
The active failure mechanism in copper depended not only on the stress state but also *on the distribution of preexisting voids*

Fracture in High-Purity Nickel: Void Nucleation



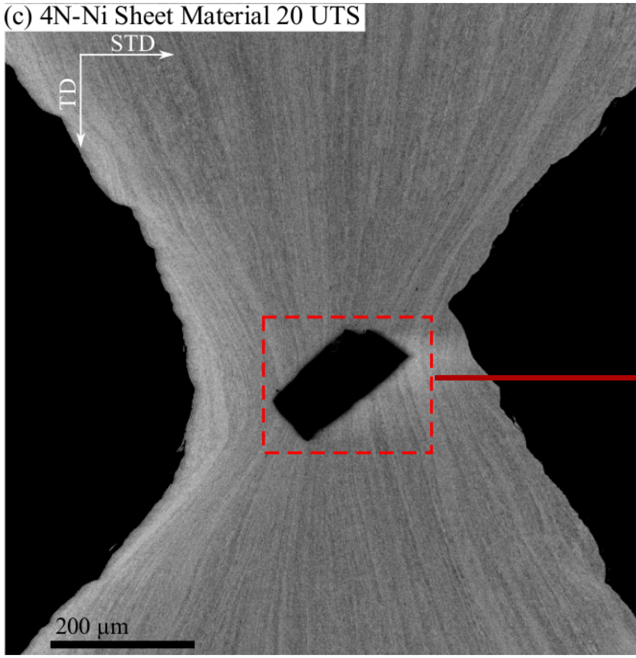


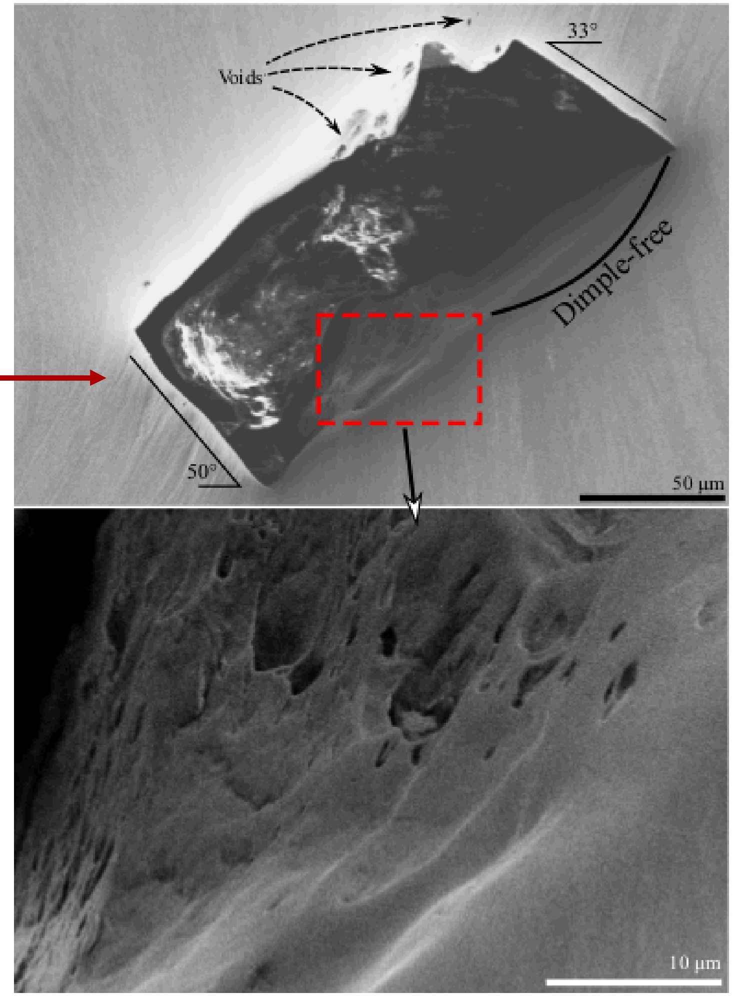
Voids only form within the shear band



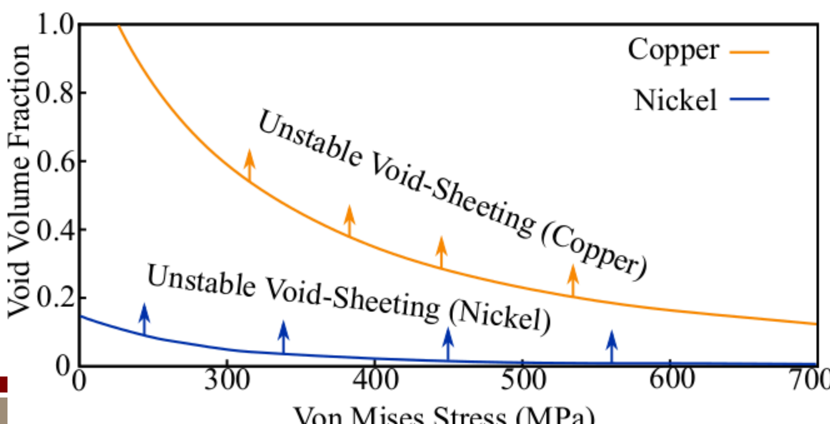
Void nucleation within the shear band is limited, and the two halves of the specimen begin to slip past each other. This creates a macroscopic crack

Fracture in High-Purity Nickel: Cavity Formation



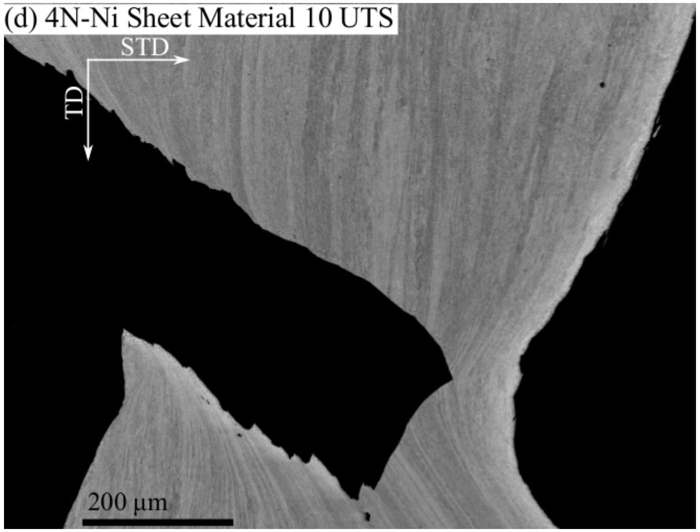


Eventually, enough voids nucleate to allow coalescence by void sheeting, and an "Orowan void" forms



A relatively small void volume is necessary for void sheeting in nickel. But since void nucleation in the shear band was limited, the entire fracture process of this material was not controlled by void sheeting

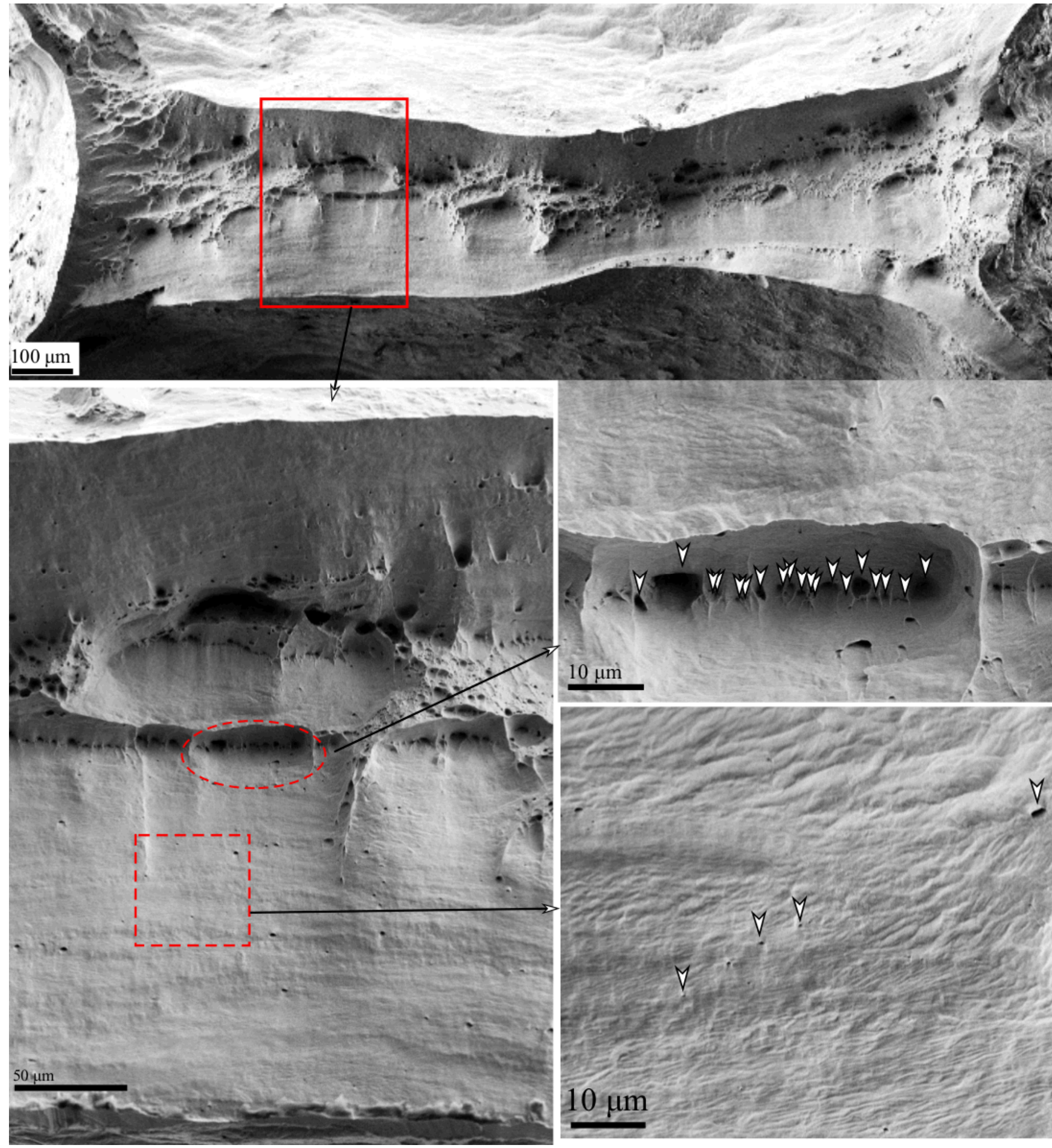
Fracture in High-Purity Nickel: Final Fracture



Final fracture is controlled by the Orowan mechanism as this cavity grows into essentially void-free material

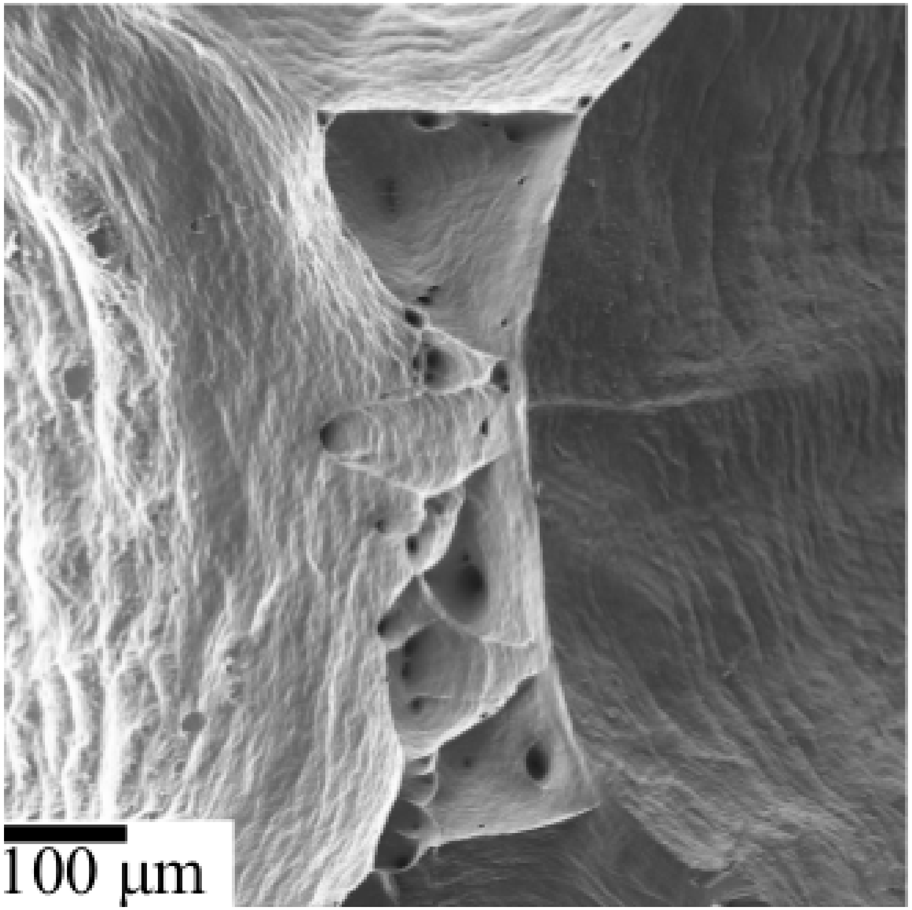
The active failure mechanism in nickel also depended not only on the stress state but also *on the distribution of preexisting voids*

The fracture surface of a high-purity nickel specimen is shown. Evidence of two failure mechanisms can be seen.

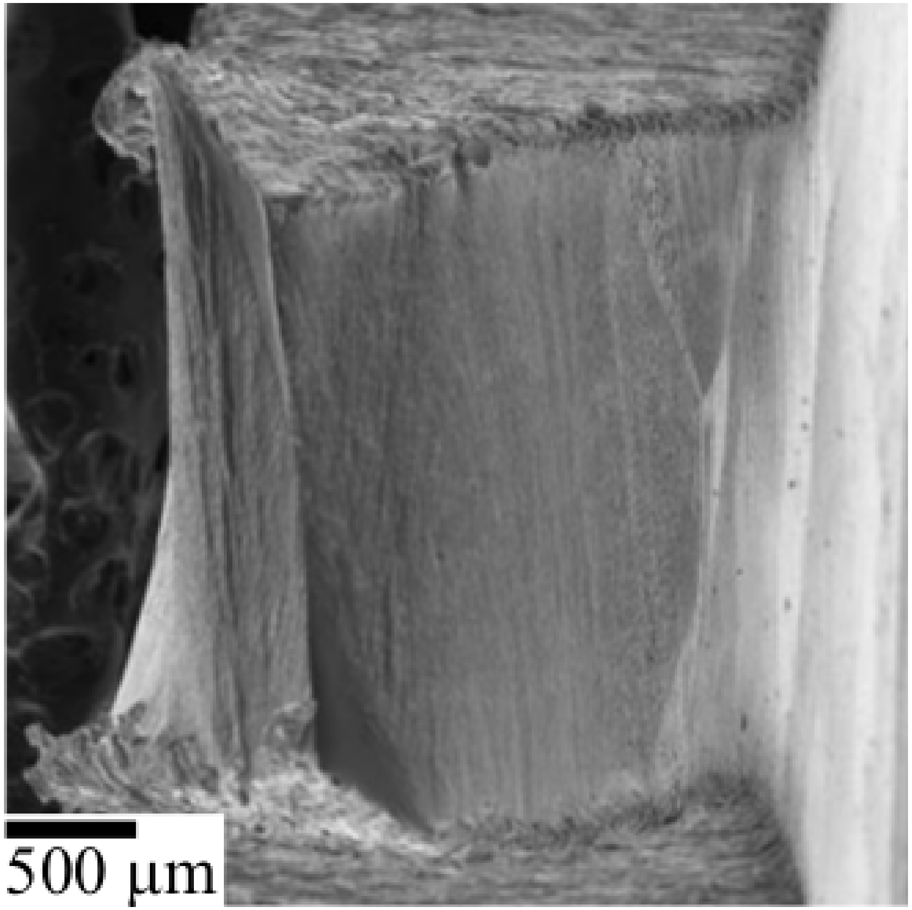


Fracture Mechanisms in Aluminum

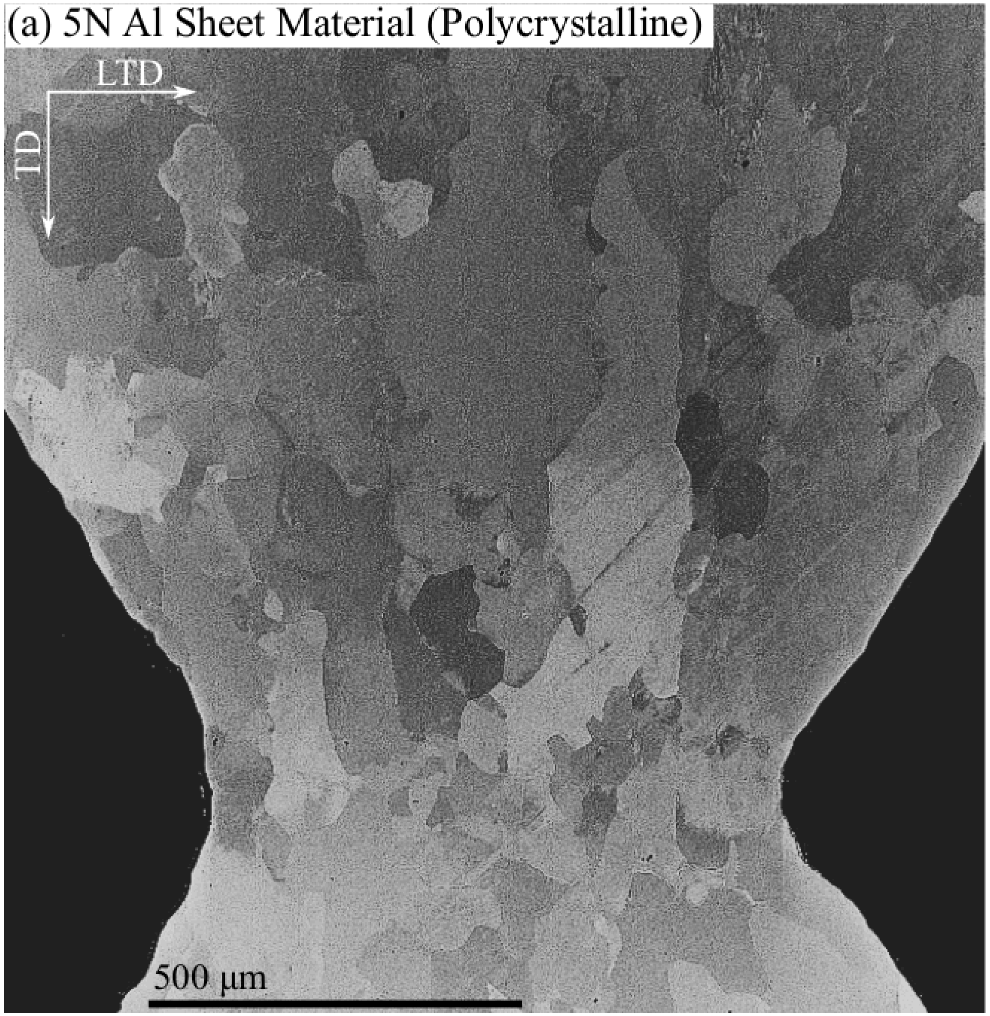
5N Al Sheet Material: Fracture is controlled by void nucleation, growth and coalescence



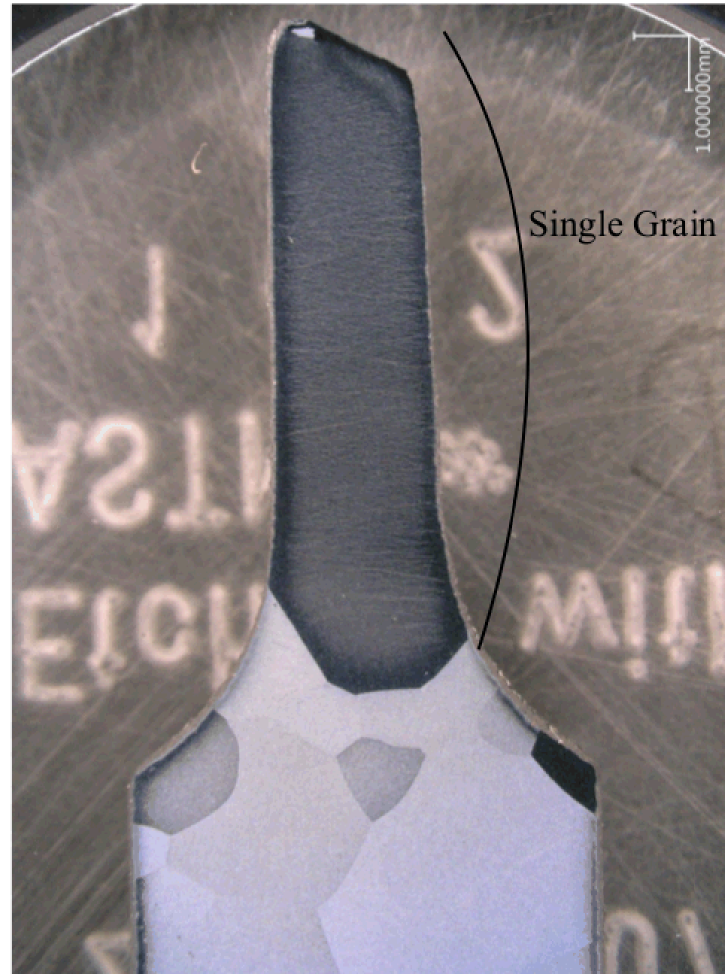
4N Al Sheet Material: Fracture is controlled by pure plasticity (necking to a point)



Void nucleation in aluminum depends on grain size



(a) 5N Al Sheet Material (Polycrystalline)

(b) 4N Al Sheet Material (Oligacrystal)


Cavitation can be entirely suppressed if the microstructural features necessary for void nucleation are removed

Conclusions

The mechanism of fracture depends on both the stress state and the void-nucleation rate and distribution of incipient voids

Cavitation can be entirely suppressed if the microstructural features necessary for void nucleation are eliminated