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Title: Influence of Grain Boundary Structure and Distribution on Dynamic (Shock) Response of Materials

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GRC Abstract

Influence of Grain Boundary Structure and Distribution on Dynamic (Shock) Response of Materials

Juan P. Escobedo-Diaz, Ellen K. Cerreta, Darcie Dennis-Koller, Curt A. Bronkhorst, Saryu Fensin, Ricardo A. Lebensohn and Davis Tonks.

Plate impact experiments were conducted to examine the influence of defect density, in this case grain boundary distribution, on the dynamic tensile response of Cu . Grain boundary distribution was altered through heat treatment, which altered grain size. The peak compressive stress was maintained at ~1.5 GPa for all experiments, low enough to cause an early stage of incipient spall damage that can be correlated to the surrounding. The quantitative post-impact metallographic analyses of recovered samples showed that for the materials with grain sizes larger than 30 μm the void volume fraction and the average void size increased with increasing grain size. In the 30 and 200 μm samples, void growth and coalescence was observed to dominate the damage behavior, whereas in 60 and 100 μm sized grains samples, most of the damage was restricted to individual, isolated voids. Electron backscatter diffraction (EBSD) observations showed that voids preferentially nucleate and grow at grain boundaries with high angle misorientation. However, special boundaries corresponding to Σl (low angle, <5°) and Σ3 (~ 60° <111> misorientation) type were more resistant to void formation.

Influence of Grain Boundary Structure and Distribution on Dynamic (Shock) Response of Materials

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GRC Seminar

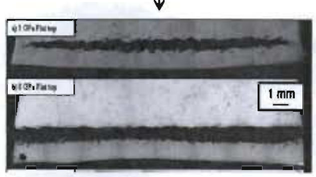
July 31st, 2011

Motivation: why dynamic (shock) response?

Damage due to dynamic failure (shock phenomena)

Vulnerability

Crash worthiness



Lab tested

Identifying the physical mechanisms responsible for dynamic material failure during shock loading provides a capability of designing and predicting material response to extreme conditions.

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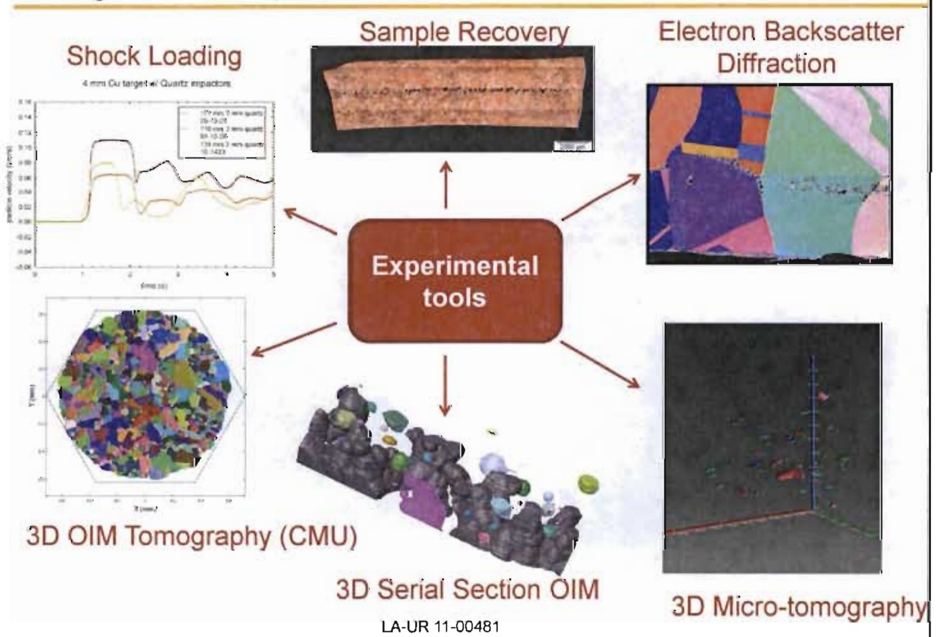
We attempt to address some key questions

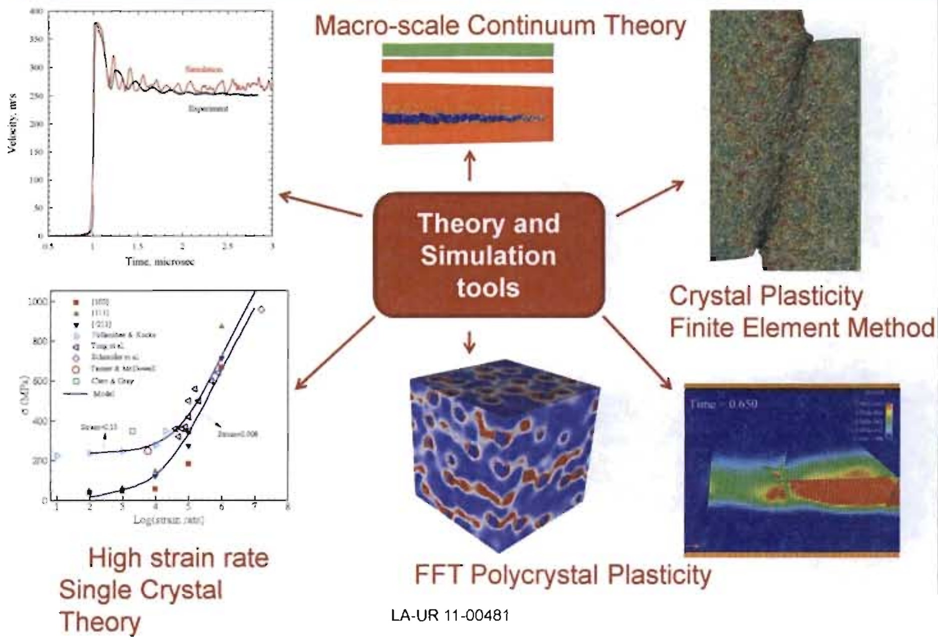
1. Can we partition deterministic processes (controllable) vs. stochastic (random) processes?
2. Can we develop a multi-scale understanding of these processes?
3. **Can we capture the essential physics in our models?**
4. **Can we control these behaviors through**

To do this, we want to understand the connections between loading environment and the characteristics of a material

Isolating Kinetic and Spatial Effects - I



Isolating Kinetic and Spatial Effects - II



Experimental Observations

Experimental configuration

In the lab: A gas gun platform can be utilized to study shock wave interactions within materials.

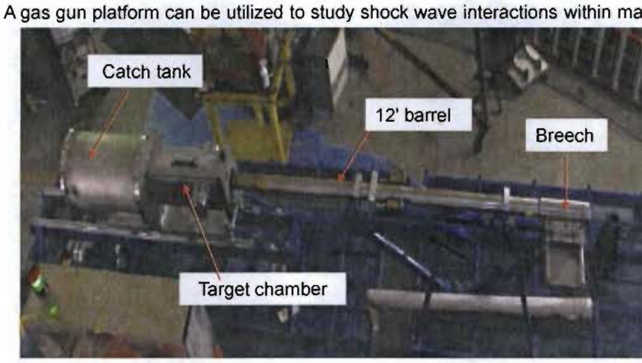
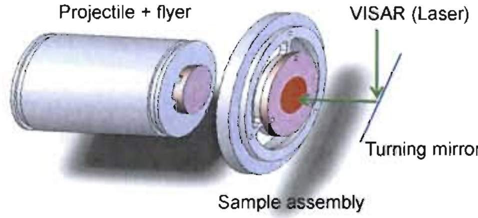


Plate impact technique



Recovered sample

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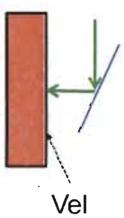
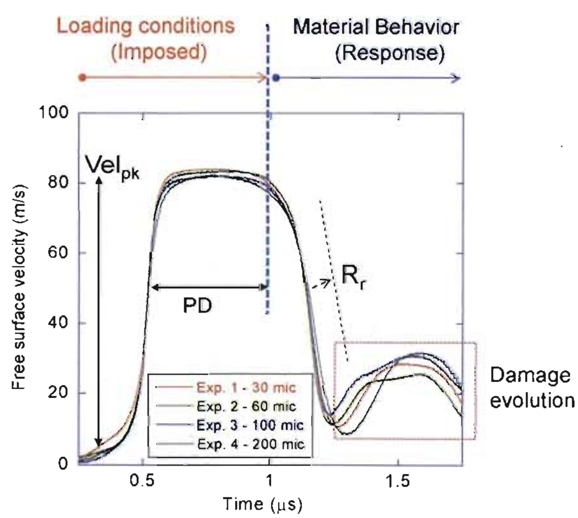
Real-time response: Free surface velocities.





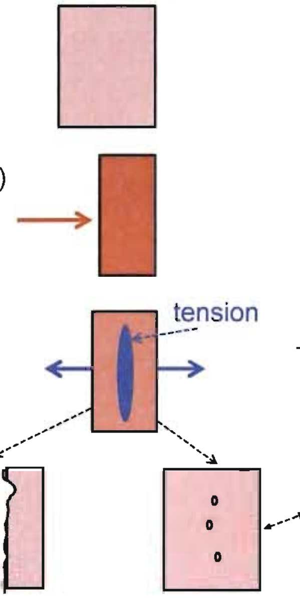
Similar loading conditions: peak velocity (Vel$_{pk}$), pulse duration(PD) and release rate(R_r).

Material response in a dynamic tensile experiment (spall)

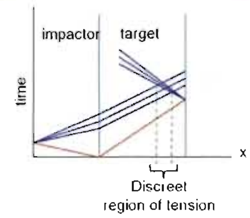
t_0: initial state

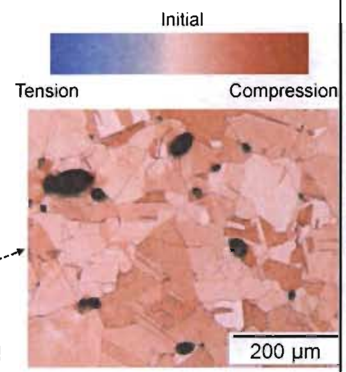
t_1: Compressed (shocked)
- * Δt: Pulse duration (< 1μs)
- * $\Delta V \leftrightarrow \sigma_c$(GPa): Peak state

t_2: De-compression
- * Release rate



Full **spall** Incipient **spall**



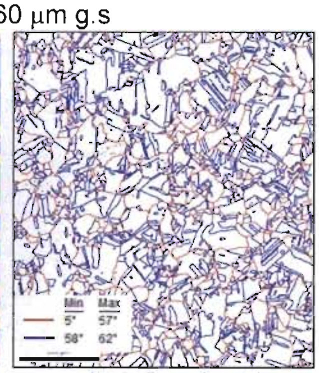


Dynamic Response vs. Grain Boundary (defects) distribution

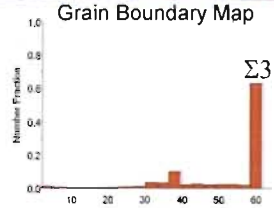
OFHC Copper (99.999%)
~ 60 μm g.s

- Grain Bound. type
- Grain Bound. distribution

Orientation Map

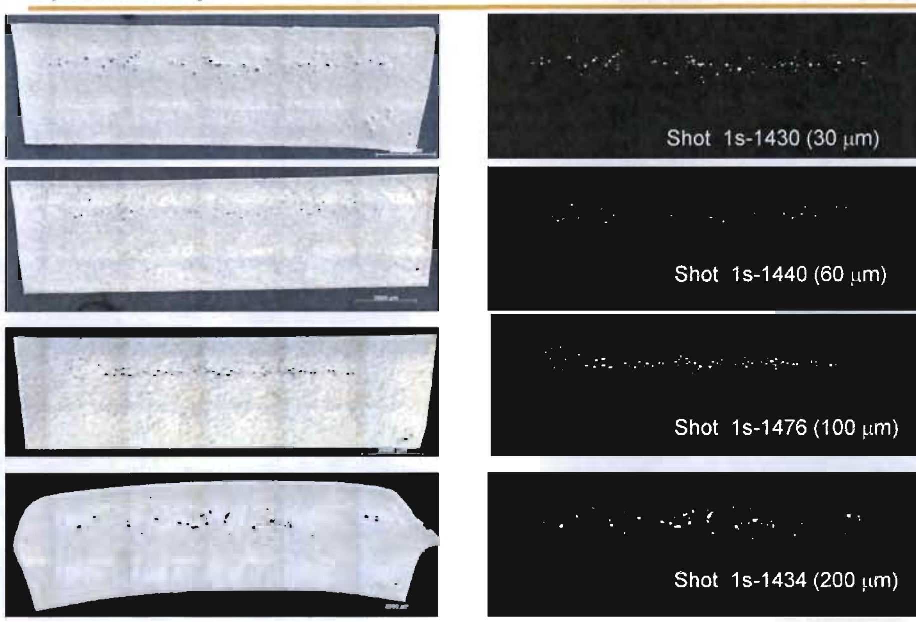


Grain Boundary Map

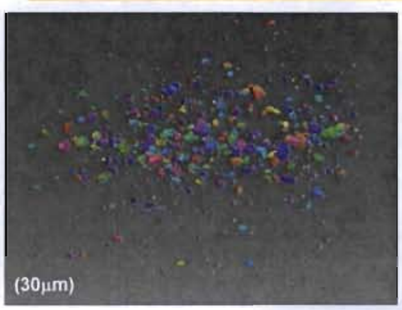


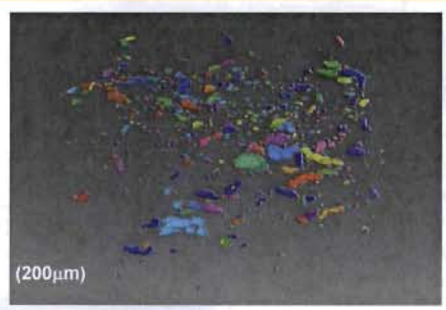
Microstructures tested
4 grain sizes: 30, 60,100, 200 μm

Optical analysis



Micro x-ray tomography

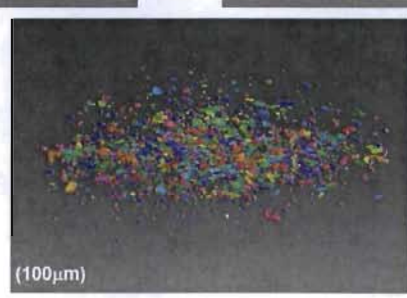




Void%

2D = 0.41

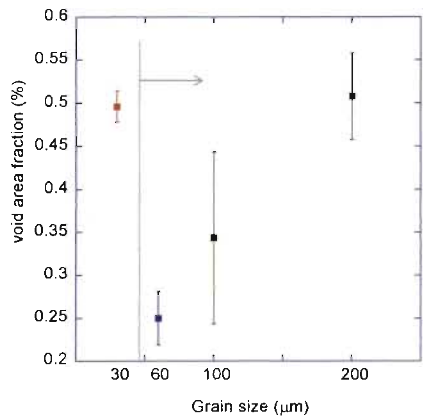
3D = 0.64



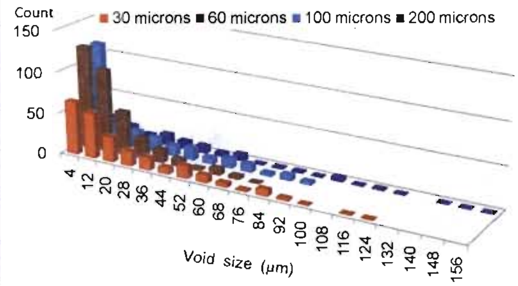
Tomography results (3D) qualitatively agree with optical (2D)

Patterson et al, Microscopy and Microanalysis, in review (2011).

Damage quantification



Void area fraction as function of the grain size



Void size distribution.

Void area fraction does not show linear trend

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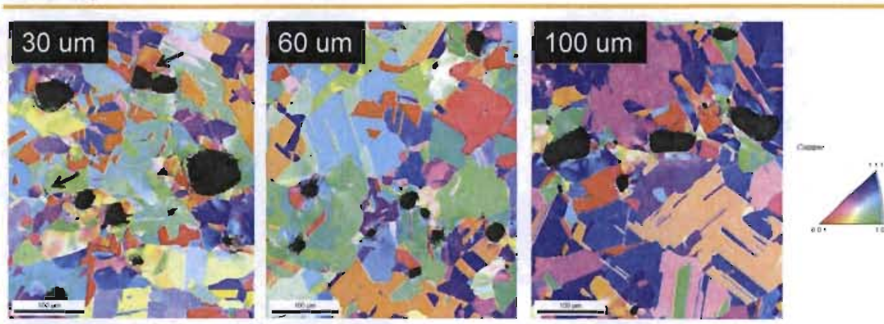
Damage characteristics



Experiment	Grain size	Number of voids	Void area fraction (%)	Avg Void diameter (um)
1s-1430	30 um	236	0.496	38.1
1s-1440	60 um	343	0.249	22.7
1s-1476	100 um	267	0.416	33.0
1s-1434	200 um	111	0.507	55.1

Damage Statistics from 2D optical analysis

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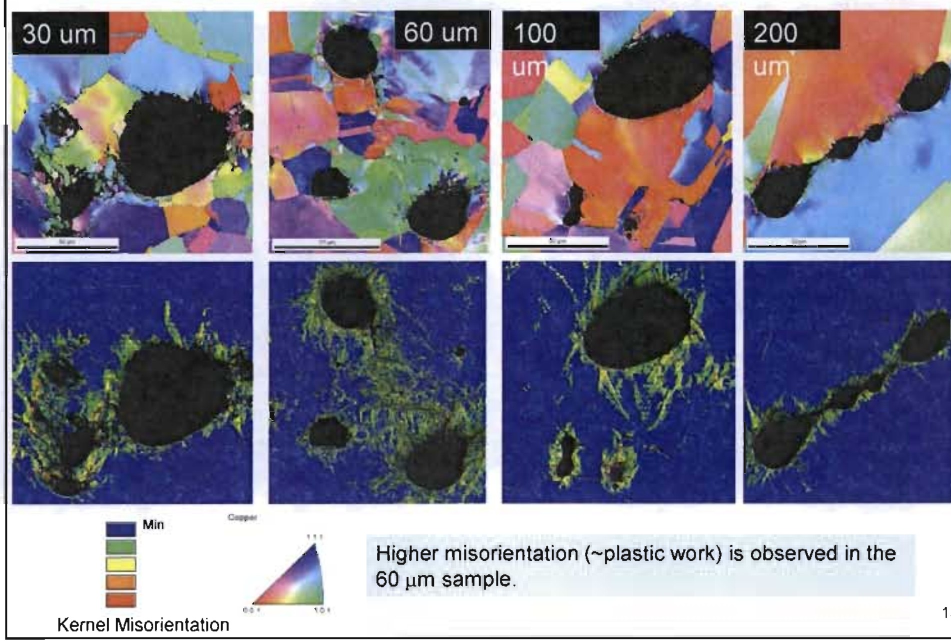
Void growth/coalescence vs. grain size



Higher misorientation (~plastic work) is observed in the 60 μm sample.

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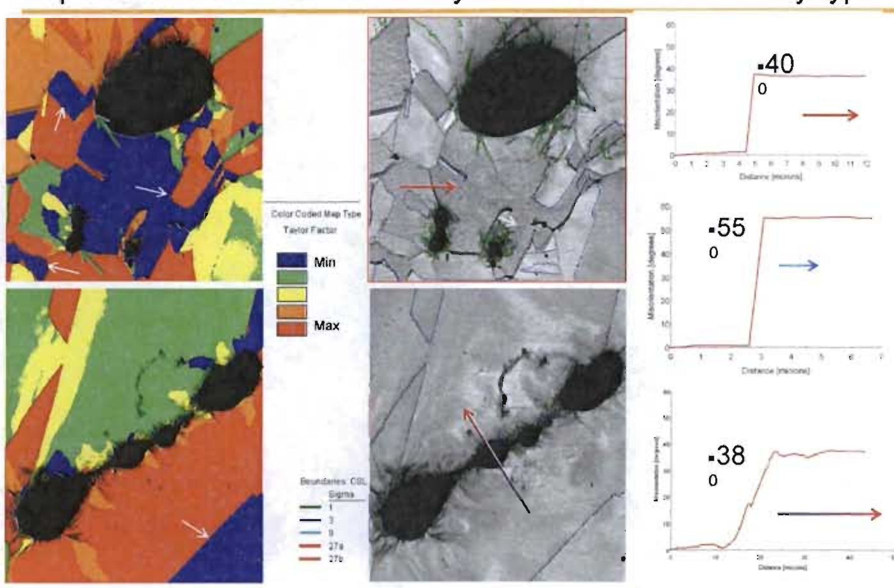
Properties from EBSD data: Taylor Factor and boundary type



Taylor Factor

G. Boundary type

Grain boundary structure as the determining factor for preferred void nucleation location.

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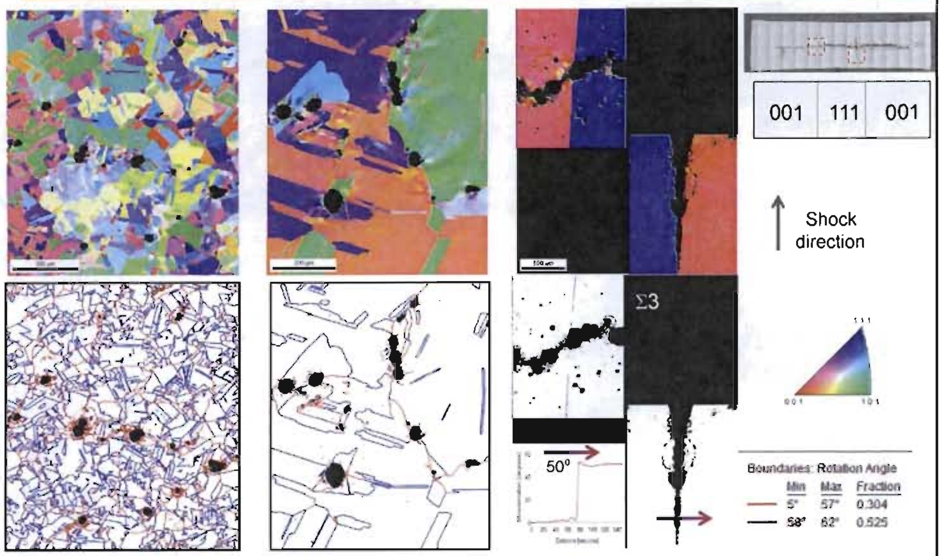
Grain boundary type



Polycrystalline (60 μm) Multi-crystalline (200μm) Columnar grained (3g)

Grain boundary ≠ Σ3 as the determining factor for preferred void nucleation location.

Main experimental findings

- **The special Σ3 (~ 60°) grain boundaries resistant to void nucleation, indicating that lattice coincidence may be important to damage mitigation.**

- **Grain size determines the spatial distribution and size of the defects (i.e. grain boundaries), inherently dictating the preferred mechanism for damage evolution:**

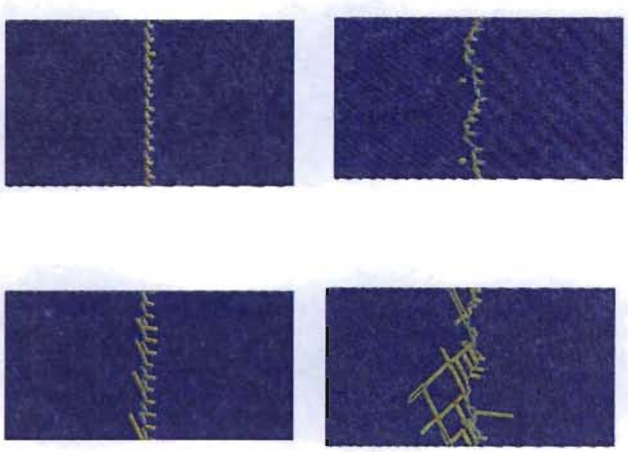
  - **Individual void growth with accompanying plastic dissipation in intermediate grain sized samples (60 μm).**

  - **Coalescence more dominant in the 200 (and 30) μm samples due to the proximity of interacting growing voids.**

Modeling Efforts

Response to Shock Grain Boundary Structure.

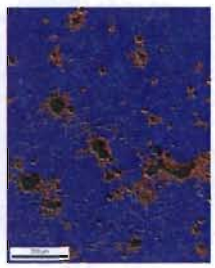
Atomistic scale



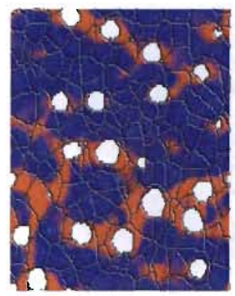
Higher generation of defects at disordered grain boundaries.

Plastic flow and void interaction

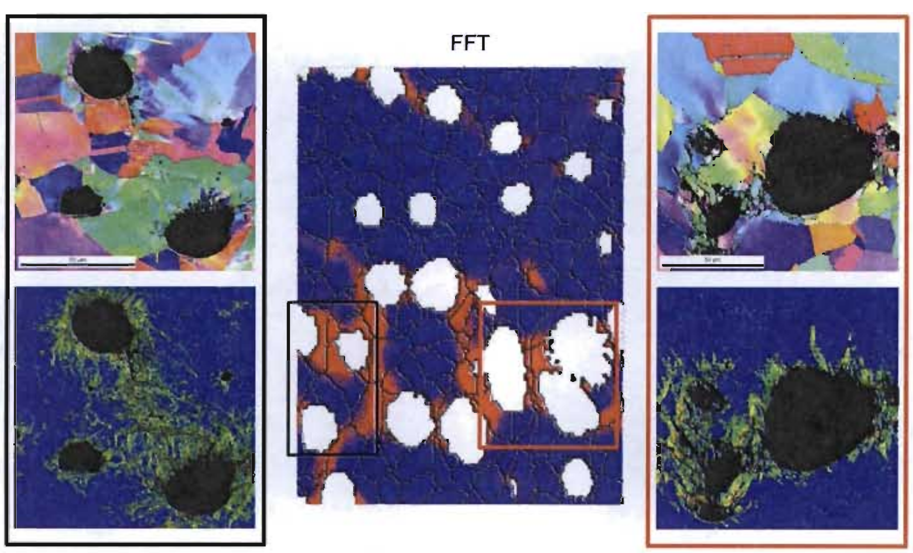
Mesoscale



EBSD Misorientation

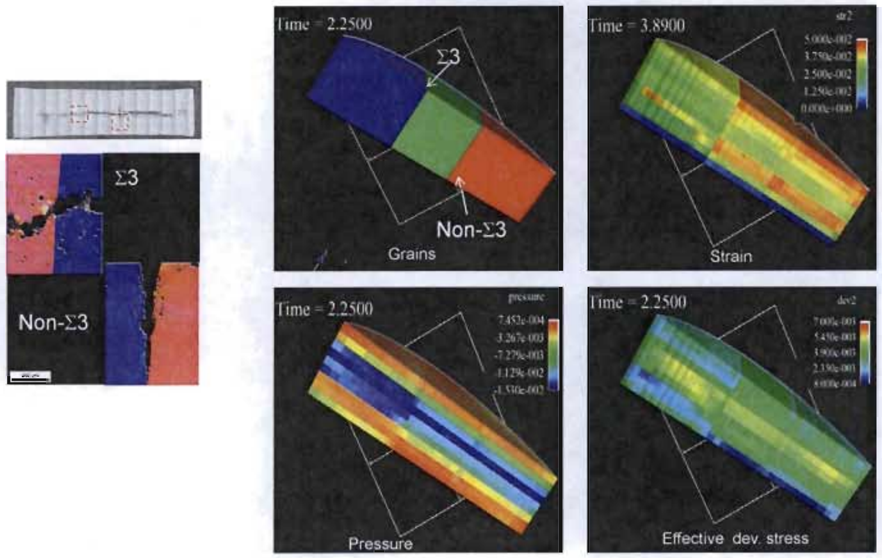


Plastic flow and void interaction



Plastic fields between voids determine damage behavior: void growth vs. coalescence.

Boundary Response to stress state



The highest calculated stress, strain and pressure gradients Σ3 boundary indicating its higher strength.

Experimental Observations

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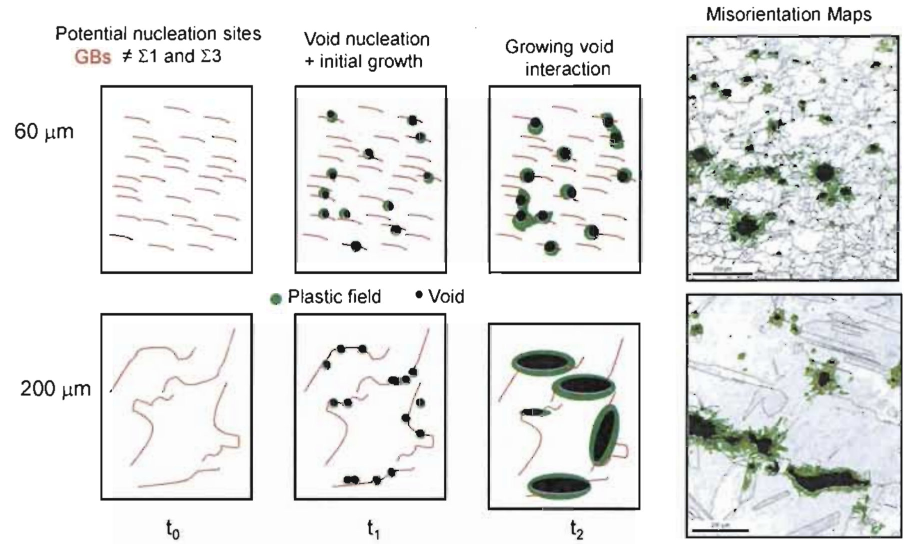
Modeling Efforts

↓

Damage mechanism

Mechanism for damage evolution



Distance between nucleated voids determines individual growth + plastic dissipation or coalescence.

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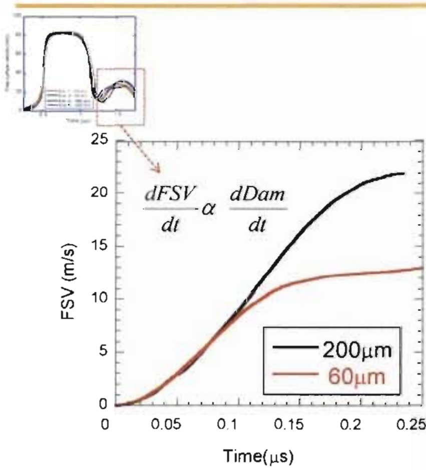
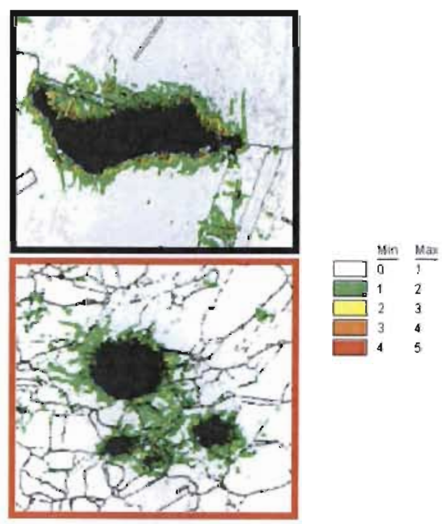
Real time response ↔ damage characteristics





$$\frac{dDam}{dt} \begin{cases} \dot{N} = \dot{N}_0 \exp\left[\frac{(\sigma - \sigma_{n0})}{\sigma_1}\right] \\ \dot{R} = \left(\frac{\sigma - \sigma_{g0}}{4\eta}\right) R \end{cases}$$

Re-acceleration rate reflects damage behavior.

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Summary

- Shock loading and microstructure are intimately connected to the dynamic material response.
- A critical length scale exists where mechanisms of ductile damage formation transition from individual void growth to coalescence dominated.
- An understanding of mechanisms dominating damage regimes is necessary to quantitatively interpret velocimetry results.