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Title: Controlled Shock Loading for Microstructural Correlation of Dynamic Damage Behavior

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Intended for: Materials Science Seminar and Colloquium
Washington State University
Pullman, WA
3/11/2011

Los Alamos
NATIONAL LABORATORY
EST. 1943

Materials Science and Engineering PhD Program Colloquium

Seminar Notice

Controlled Shock Loading for Microstructural Correlation of Dynamic Damage Behavior

Materials performance is recognized as being central to many emergent technologies. Future technologies will place increasing demands on materials performance with respect to extremes in stress, strain, temperature, and pressure. In this study, the dynamic ductile damage evolution of OFHC Cu is explored as a test bed to understand the role of spatial effects due to loading profile and defect density. Well characterized OFHC Cu samples of 30 μm, 60 μm, 100 μm, and 200 μm grain sizes were subjected to plate impact uniaxial strain loading at 1.5 GPa. This spall geometry produced early stage (insipient) damage in the Cu samples that could be correlated to microstructural features in metallographic analysis. The recovered damaged microstructure was examined using traditional 2D metallographic techniques (optical and electron microscopy) as well as 3D x-ray microtomography. Calculated spall strength from the free surface velocimetry (VISAR) showed no change with respect to changes in grain size, however, the magnitude of the peak after the first pull-back as well as rate of re-acceleration are dependent on grain size and can be correlated to damage observed in the recovered samples. These results reveal a critical length scale for the transition from a nucleation dominated regime to a growth dominated regime for the damage evolution process. The results show that for samples with small (30 μm) and large (200 μm) grain sizes the growth of voids is dominated by coalescence, whereas for medium (60 μm and 100 μm) grain sizes the growth is restricted to a much slower process of individual void growth. Electron backscatter diffraction reveals that voids preferentially nucleate at grain boundaries with high misorientation angles while special boundaries (low angle ∑1 and high angle ∑3) proved to be resistant to void nucleation. Based on these findings, mechanisms for the void nucleation/growth and coalescence are proposed.

Date: **March 11, 2011**

Time: **12:10 pm**

Location: **ETRL 101**

Presented by:

Dr. Darcie Dennis-Koller,
R & D Scientist
Los Alamos National Laboratory

Pizza will be provided at 11:50 in ETRL 119

Darcie Dennis-Koller is an R&D scientist from Los Alamos National Laboratory specializing in experimental studies of dynamic materials response toward improving our understanding of materials in extreme environments. Darcie's research interests include dynamic damage evolution in materials under high strain, high strain rate shock loading conditions, metals equation of state, advanced diagnostics, ejecta phenomena, and emerging experimental techniques pertaining to shock compression science through the use of light gas guns, powder guns, HE drive, and shock recovery. She has published works on shock wave shaping techniques, dynamic response of materials such as uranium, copper, aluminum, steel, lead, and various granular materials, as well as isentropic compression methods and radiance measurements. She serves on several review panels for materials in extreme environments, currently leads a large LANL basic science project for targeted studies on the influence of spatial and kinetic effects on damage initiation and growth and has awards including a 2006 Defense Programs Award of Excellence. Darcie received her Ph.D in 2003 from Colorado School of Mines in Materials Engineering and completed a postdoctoral appointment in the Dynamic Materials group at LANL. She is currently in the Weapons Experiments (WX-9) group at LANL.

For information contact Diane McGarry, msep@wsu.edu
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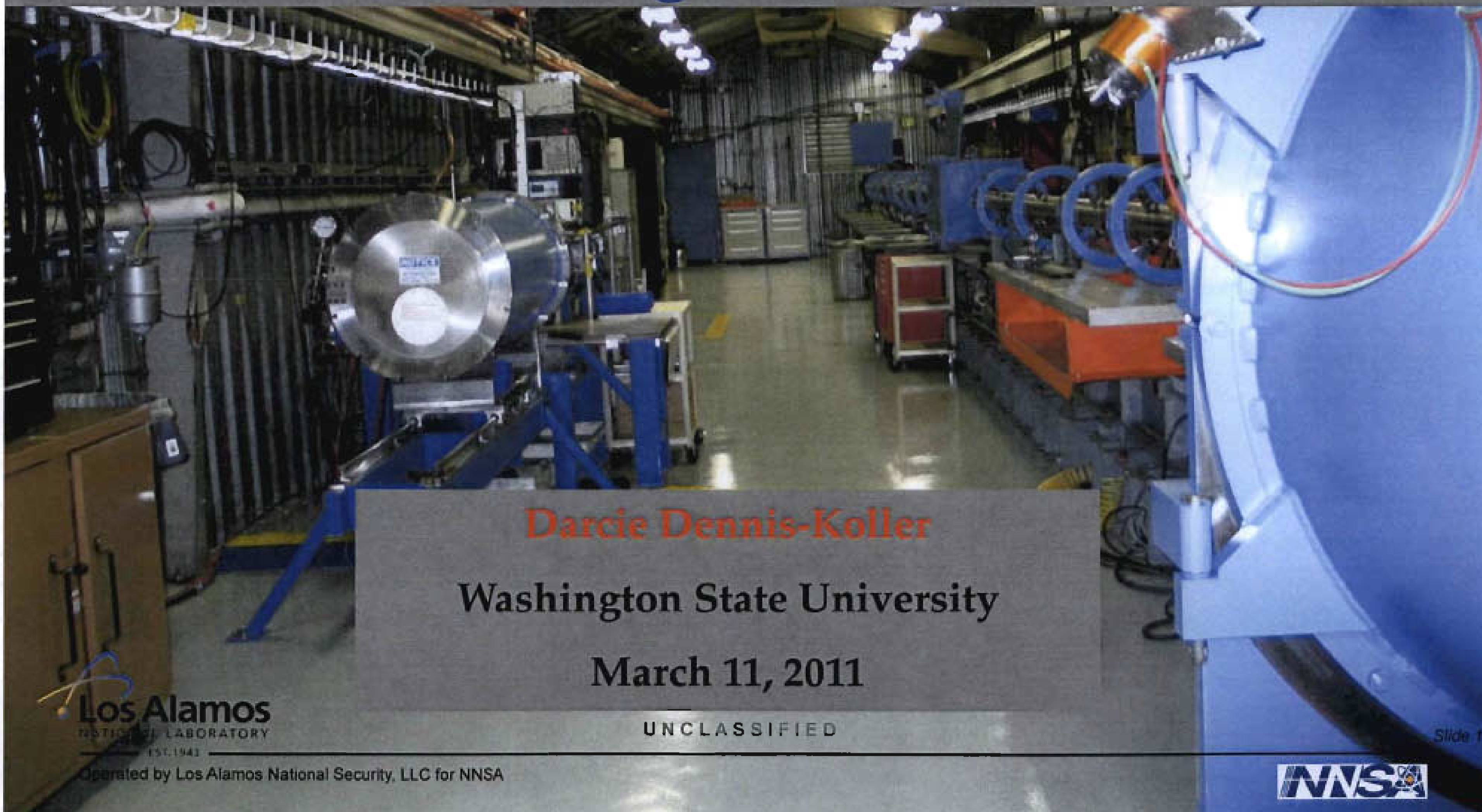
WASHINGTON STATE UNIVERSITY

Controlled Shock Loading for Microstructural Correlation of Dynamic Damage Behavior



Darcie Dennis-Koller

Washington State University

March 11, 2011

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Experimental activities in Shock and Detonation Physics at Los Alamos enable realistic simulations of material systems.

Fundamental Experiments

↓

Development of Physics-based models

↓

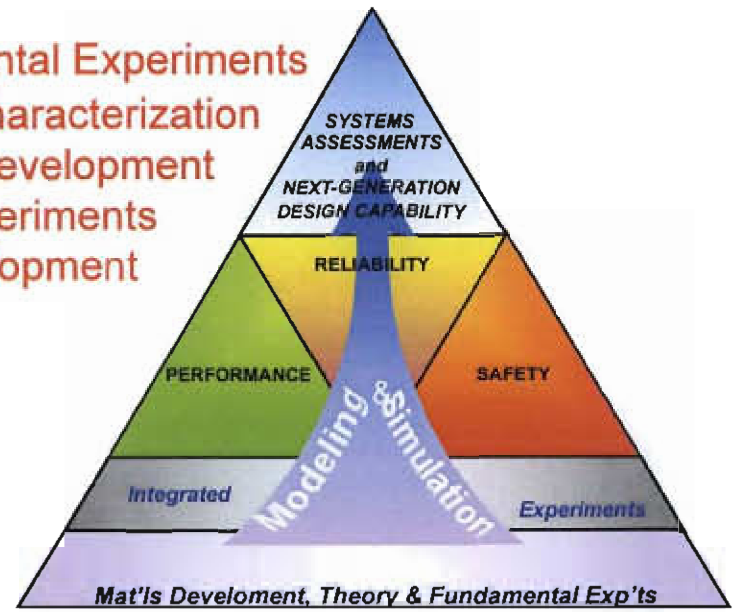
Validation of models & Hydrocode calculations ← **Integrated Exp'ts**

↓

Simulations of Integrated systems

The Shock and Detonation Physics Group is involved in:

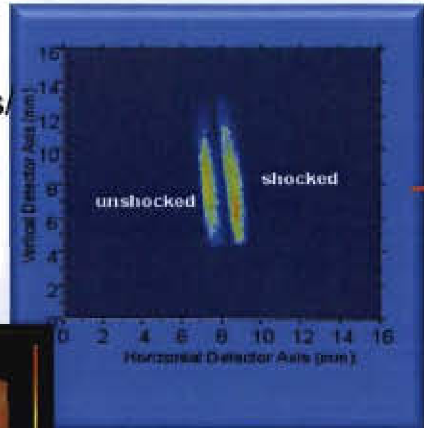
- Fundamental Experiments
- Material Characterization
- Diagnostic Development
- Integrated Experiments
- New model development

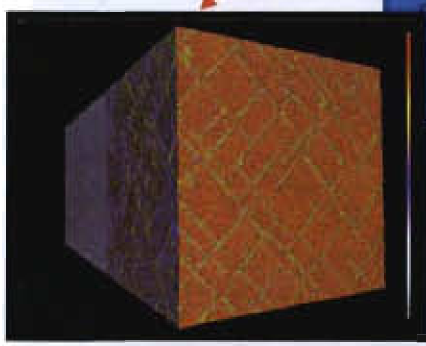


Underlying Research theme is "Materials Properties under Extreme Conditions"
Pressure, Temperature, Strain Rate, Chemistry

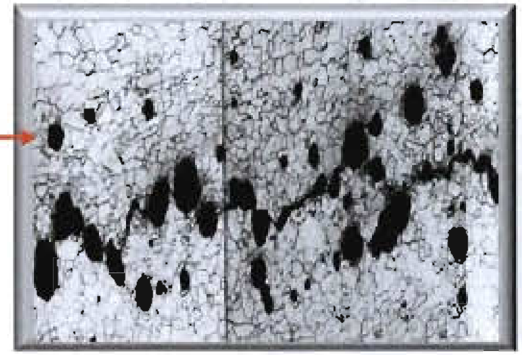
Shock physics experiments are essential to fundamental scientific materials studies.

Micro-scale –
Atomistic Calculations/
Dynamic XRD





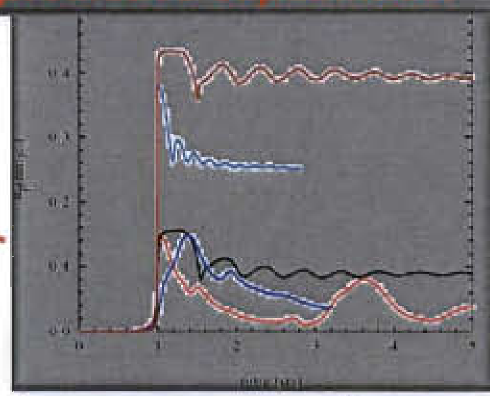
Meso-scale – Shock Recovery



Continuum scale –
VISAR/Gas Gun
Experiments

This work ultimately supports our fundamental understanding of materials by enabling high-fidelity predictive capabilities.

Data



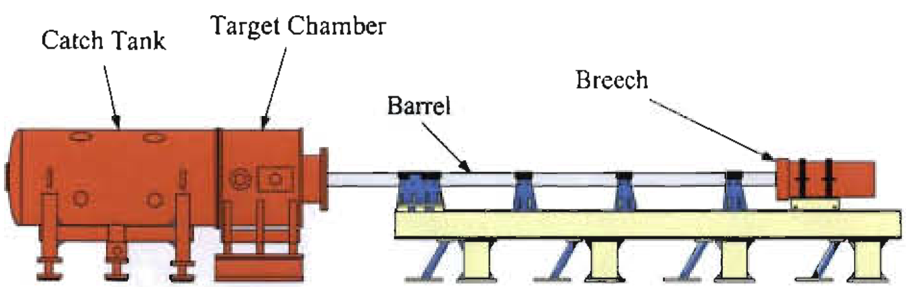
• Physics models in large scale computer simulations

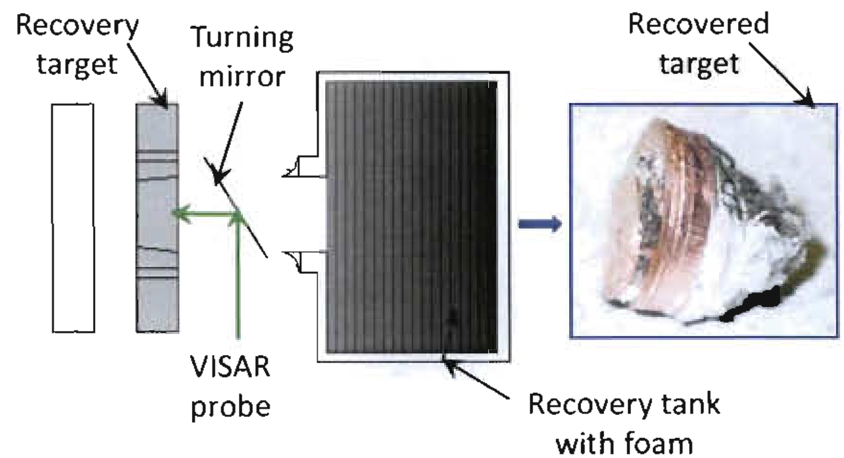
What is a Shockwave and How Does it Alter materials Properties?

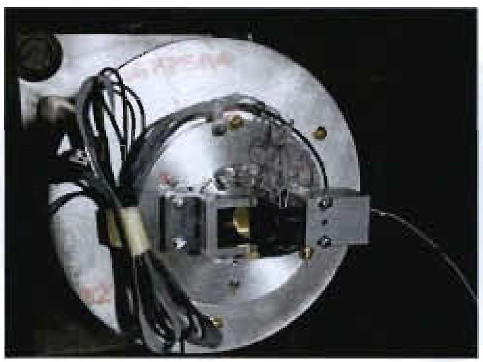
A shockwave is a discontinuity traveling through a material where the material in front is undisturbed and the material behind it is compressed and deformed. There is not a smooth transition between the two states.

A shockwave passing through a material alters the materials properties by evolving defects and damage

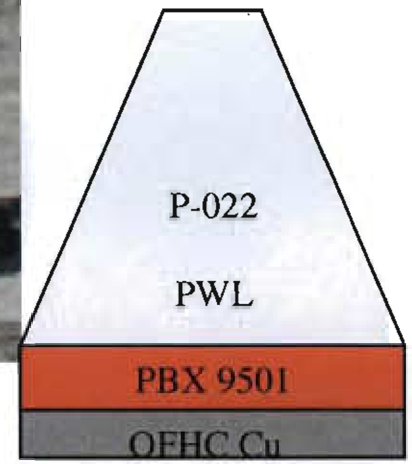
Techniques used to study dynamic response of materials. How do we put a shock into a material?







Explosive techniques provide a lot of bang for the buck.



Plane wave lens HE drive provides higher peak pressures while still providing uniaxial loading conditions.

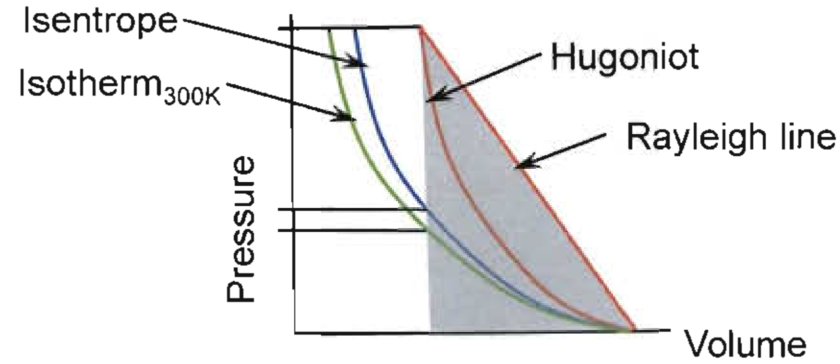
Why do we do plate impact experiments?

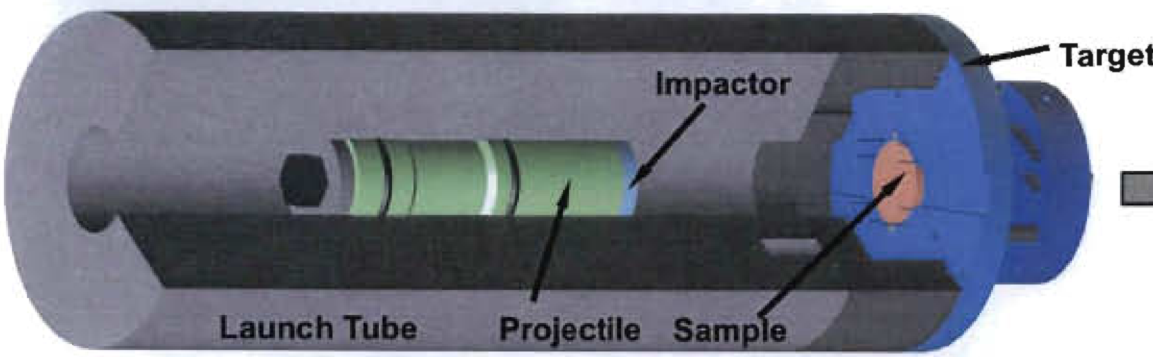
Rankine-Hugoniot jump conditions are a set of 3 equations and 5 unknowns:

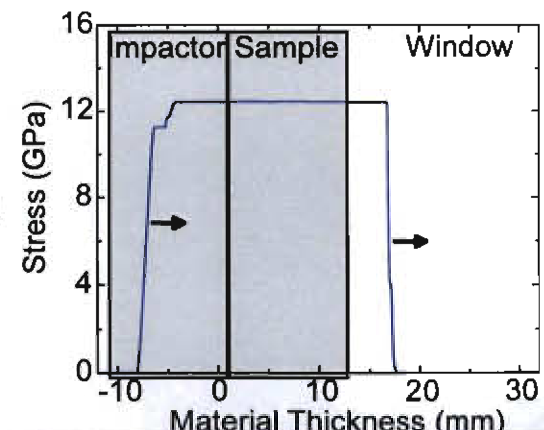
$$\rho_0 U_S = \rho(U_S u_p)$$ *conservation of mass*

$$P - P_0 = \rho_0 U_S u_p$$ *conservation of momentum*

$$P_0 u_p = \left[(E - E_0) - \frac{u_p^2}{2}\right]\rho_0 U_S$$ *conservation of energy*



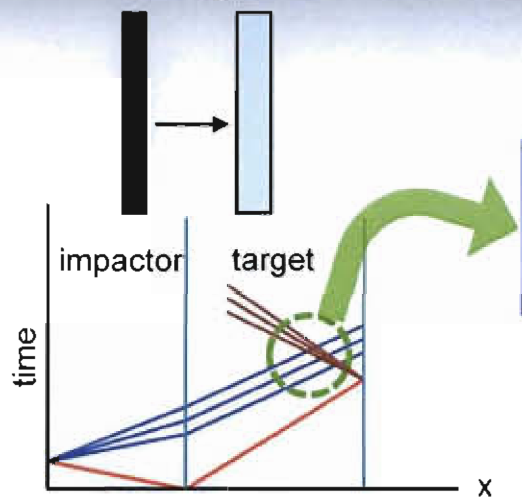




1-D strain condition allows investigation of fundamental physics of complex, shock-induced phenomena such as solid-solid and solid-liquid phase transformations and dynamic strength and damage of materials subjected to extreme stress and strain-rate conditions

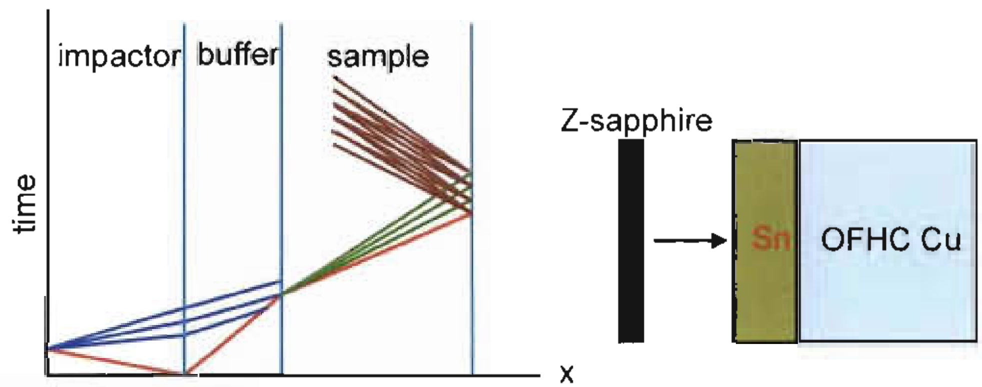
Proton radiography has been used to make direct density measurements.

Experiments are designed to produce a dynamic state of tension damaging the material.



Wave interactions in the material place the material in a localized state of tension which can exceed the tensile strength of the material and lead to damage.

Flat top spall experiment



Triangle wave spall experiment

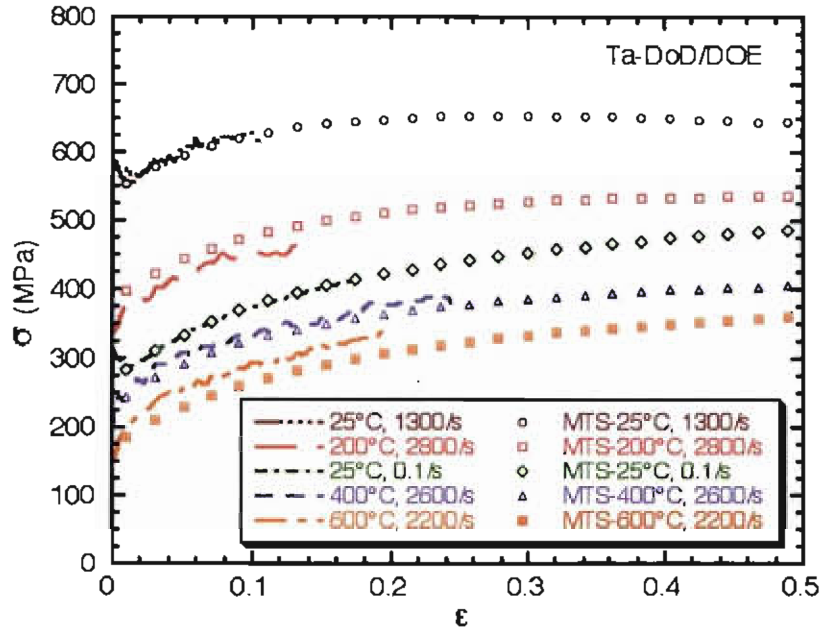
- HE loading has triangular wave shape (Taylor wave)
- Duration of release in plate impact experiment differs from that of a real Taylor wave; much shorter in the gun
- Accomplished through an overtake experiment using a Tin buffer

We attempt to address some key science 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 control these behaviors through processing?
4. Can we capture the essential physics in our models?

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

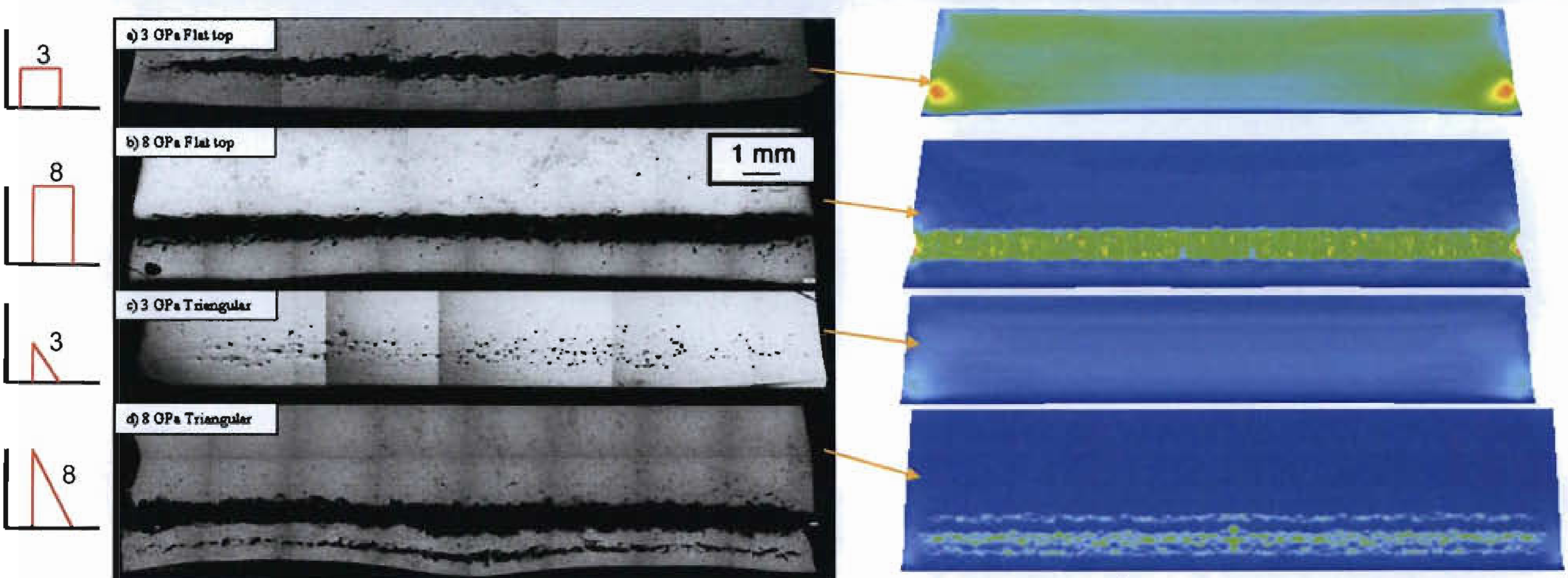
Typical Materials Characterization is at Low or Moderate Strain Rates

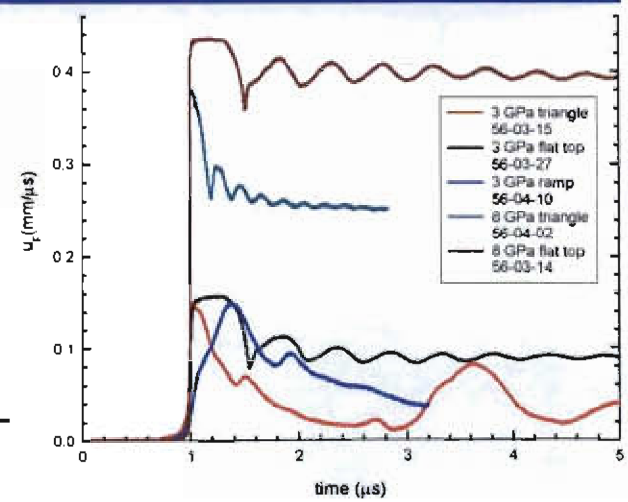


S.R. Chen and G.T. Gray III, Metall. & Matls. Trans., vol. 27A, (1996), pp. 2994-3006."Constitutive Behavior of Tantalum and Tantalum-Tungsten Alloys"

- These data frequently show that material response in dependent on strain rate
- Good understanding up to 10^3/s
- Would like to extend that understanding to 10^5-10^7/s
- These data are extrapolated to high strain rates to predict dynamic failures

Shockwave Shape Significantly Influences Damage Evolution in a Metal



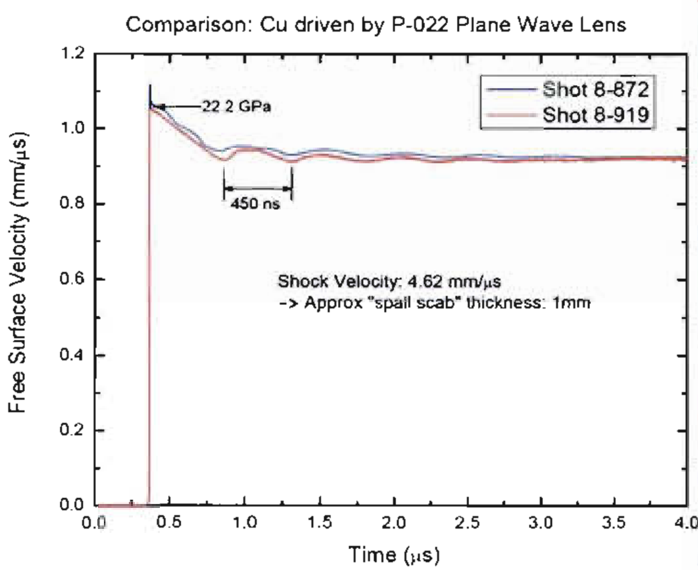


These simulations illustrate current damage model capabilities

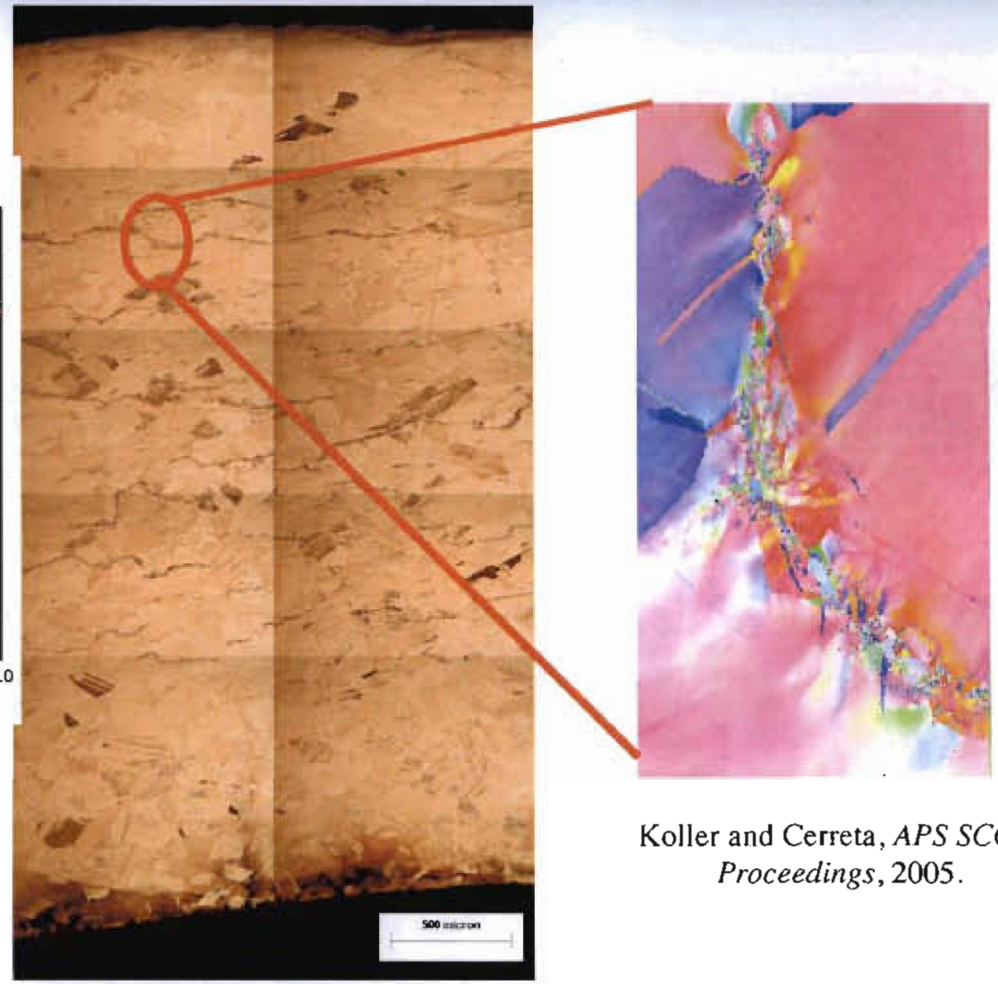
Koller and Cereta, *J. Appl. Phys*, Nov. 2003

Harstad et. al, *Plasticity Proceedings*, Jan 2009.

Under High Explosive Loading our Previous Understanding was Not Validated



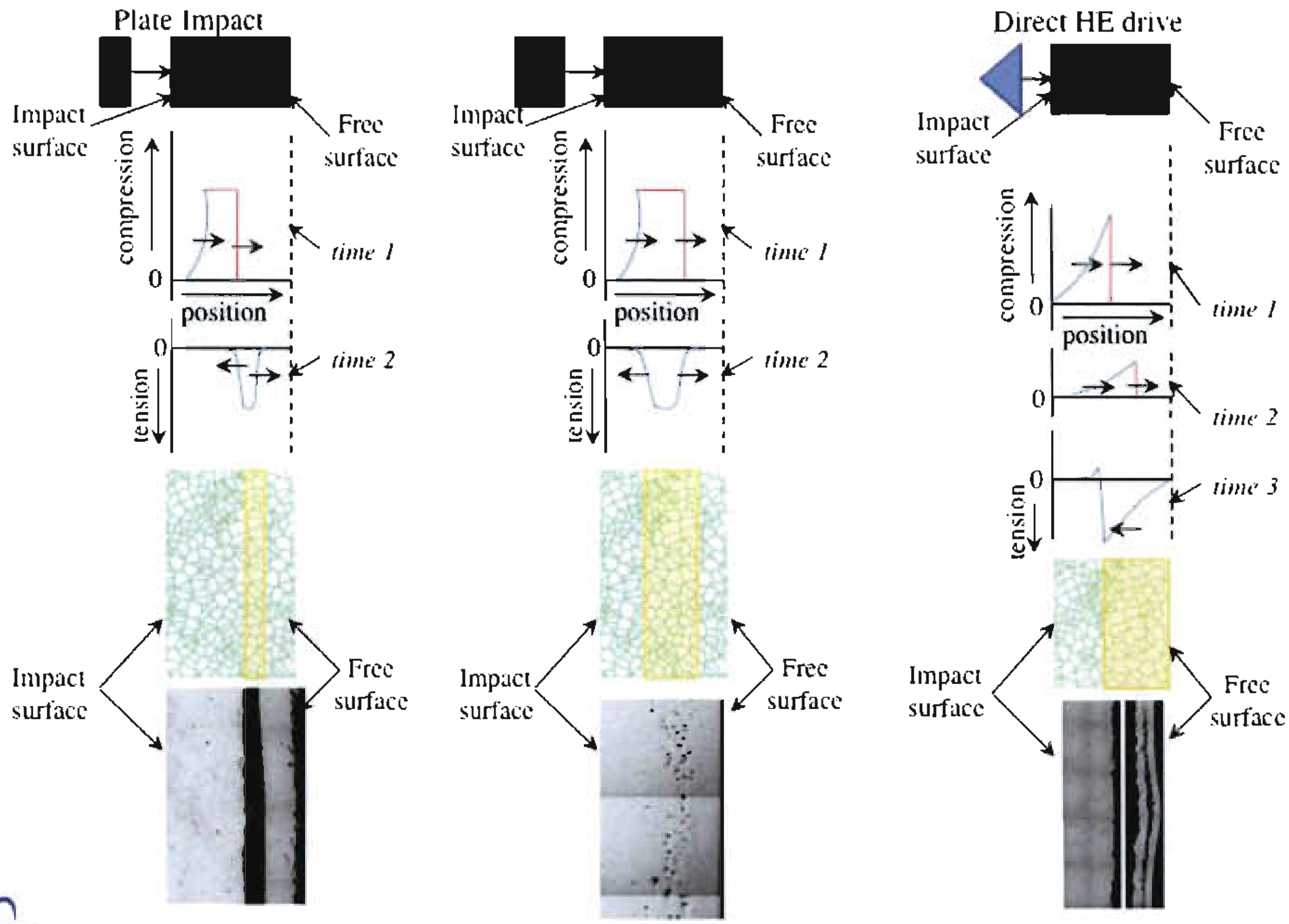
Peak Pressure = 22GPa
Direct HE



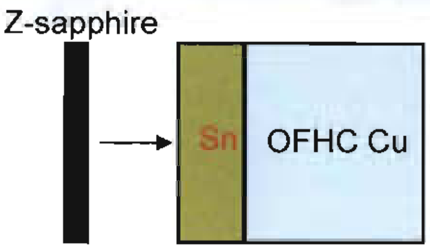
Koller and Cerreta, *APS SCCM Proceedings*, 2005.

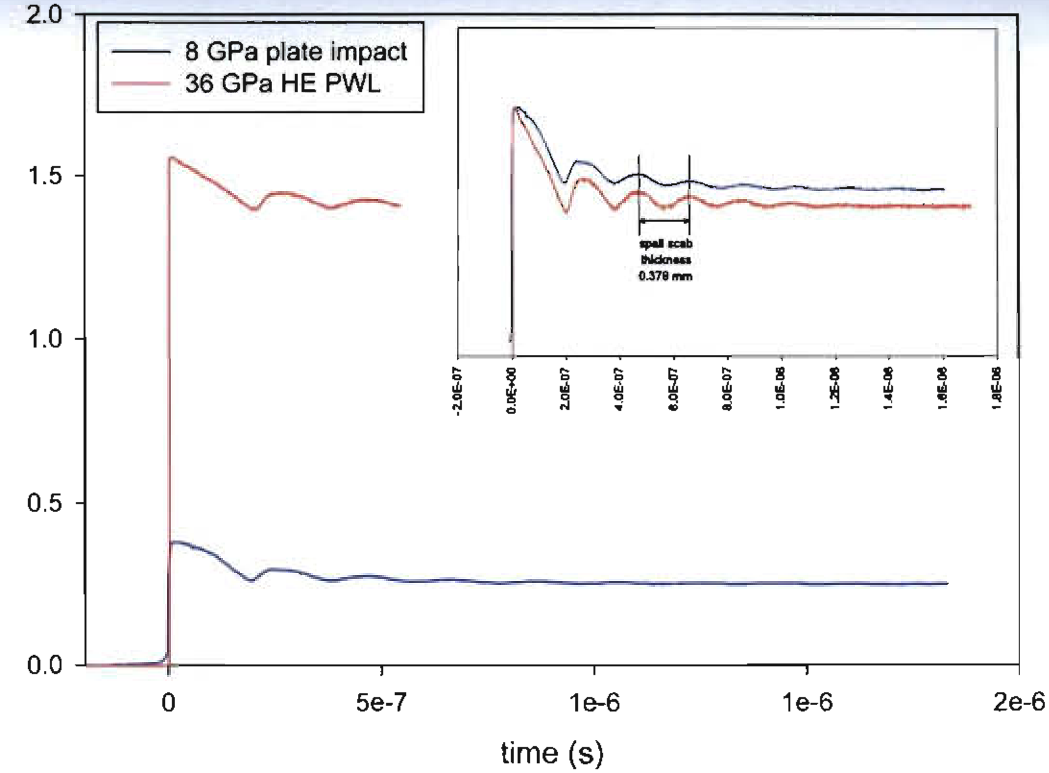
Hypothesis: kinetic and spatial parameters have an important role in dynamic damage evolution

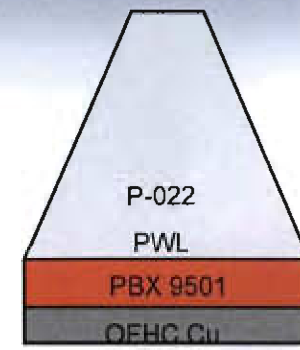
Changes in shock wave shape also result in changes in the evolution of the stress profile applied to the microstructure.



Complex loading can provide an avenue to explore the effects of peak pressure on the damage evolution.

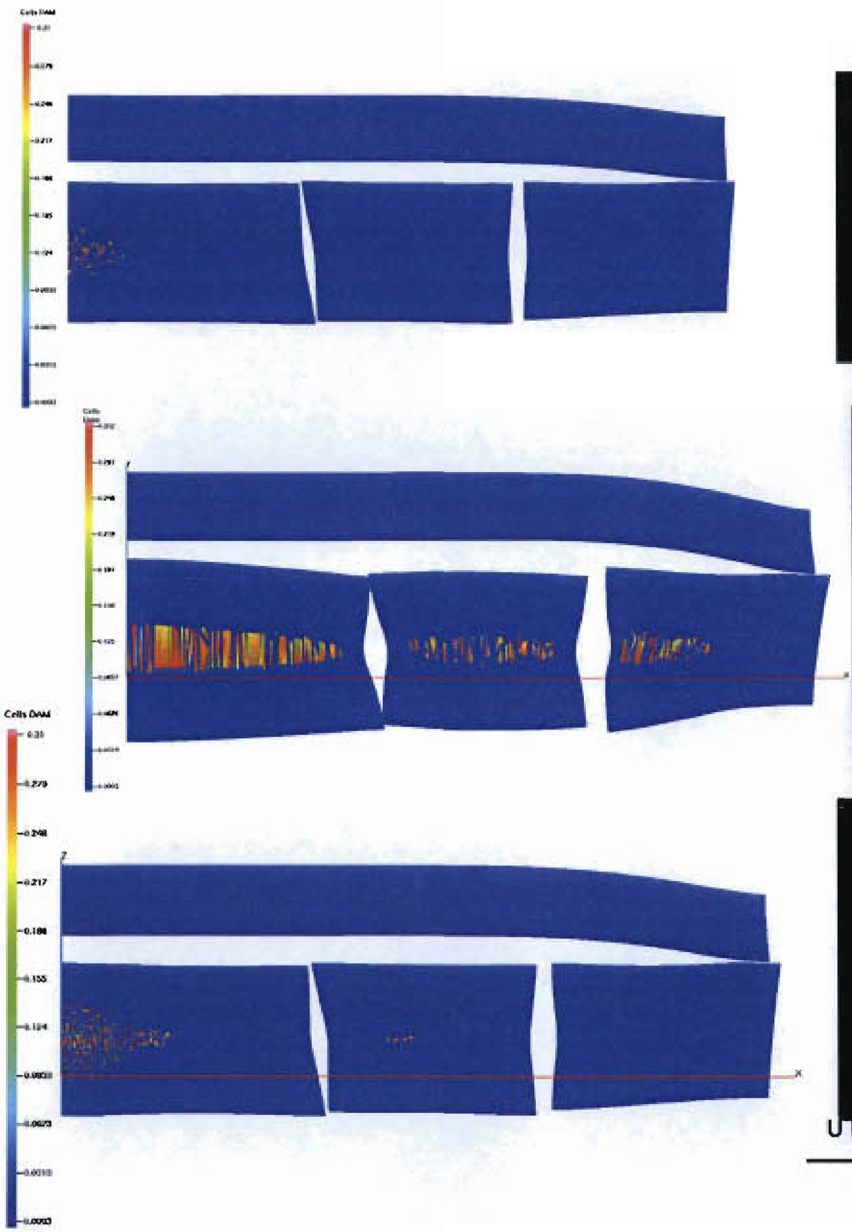


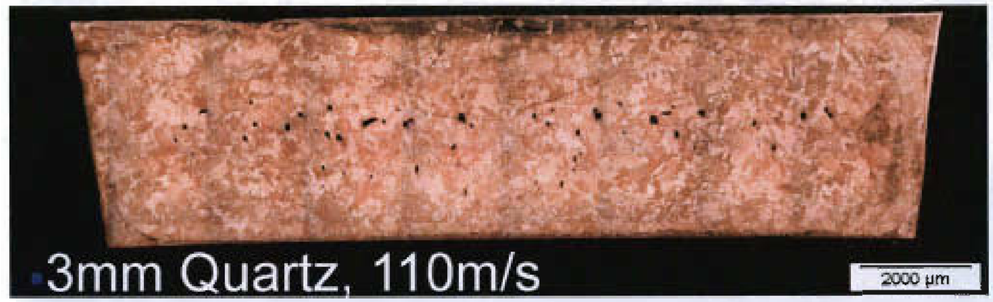




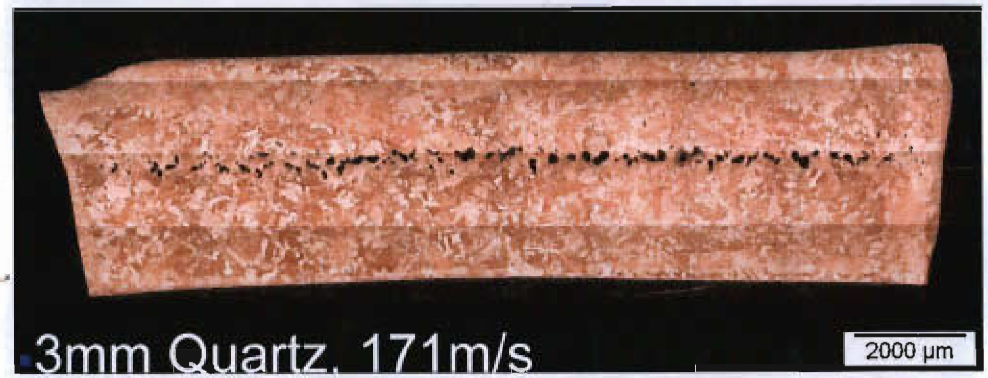
- Experiment shows that plate impact experiments can used to explore a range of peak pressure states while maintaining the same strain rate on the release.
- When the 9501 booster was added the duration of the tensile pulse was shortened and the material spalled just as was seen in the plate impact experiment using a triangle wave with a similar strain rate on release.

Scoping Calculations and Determination of Early Stage Damage





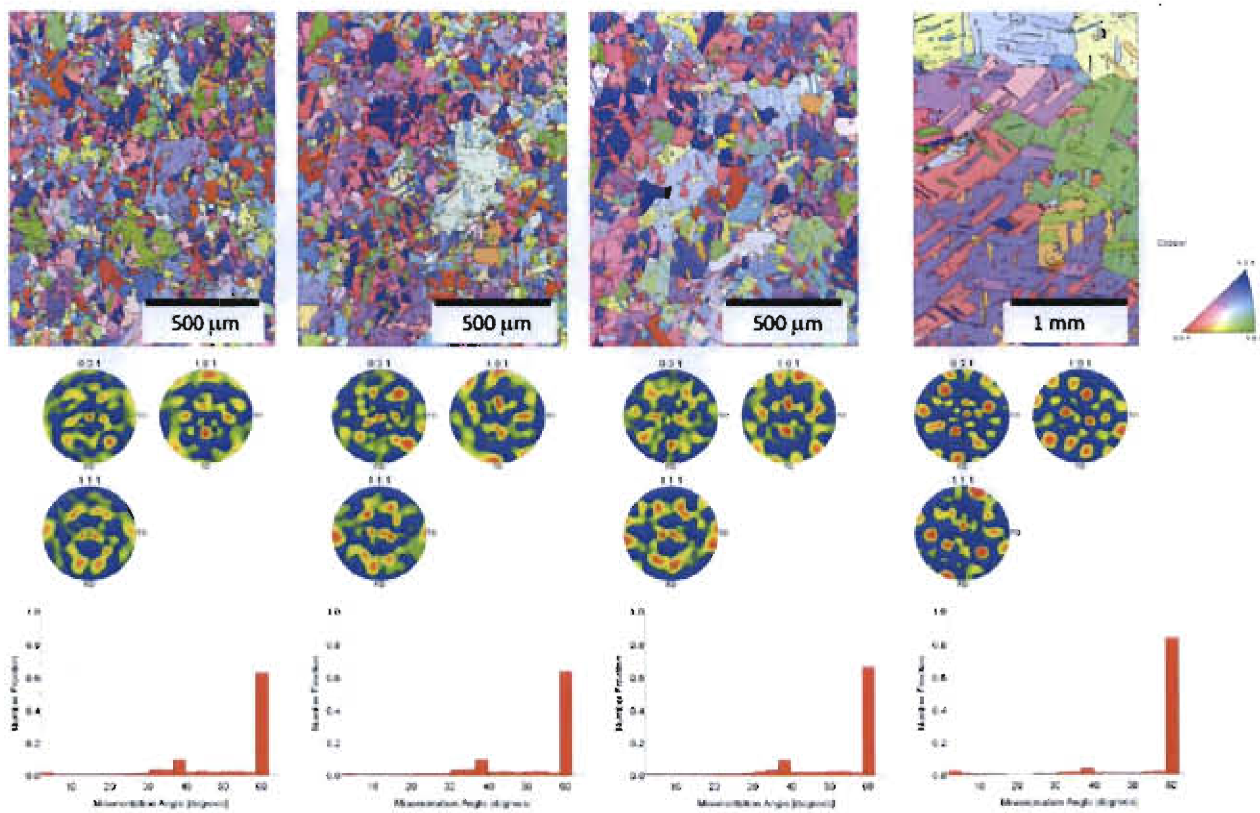
3mm Quartz, 110m/s



3mm Quartz, 171m/s

2mm Quartz, 131m/s

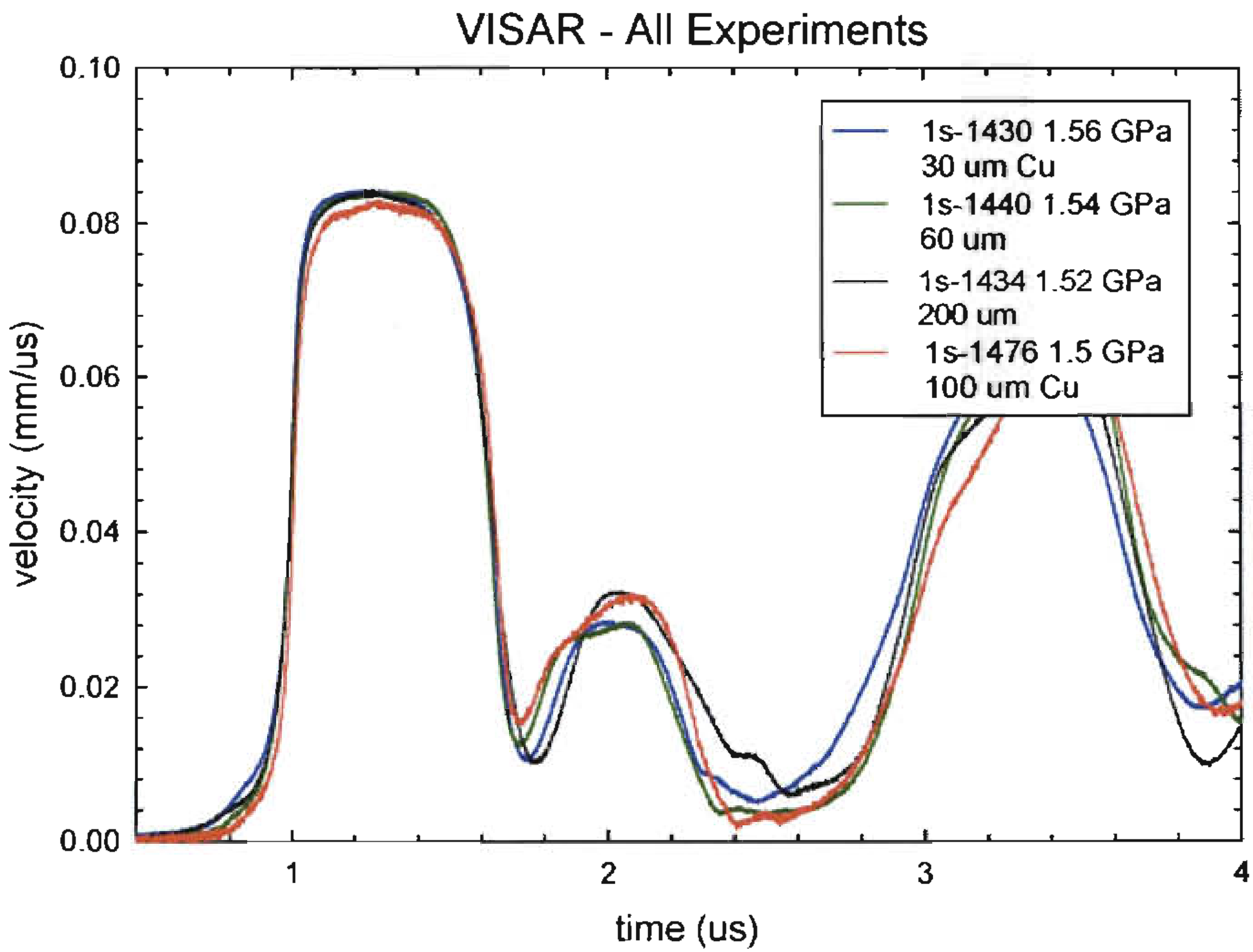
We started with some well characterized Cu material of well known grain sizes



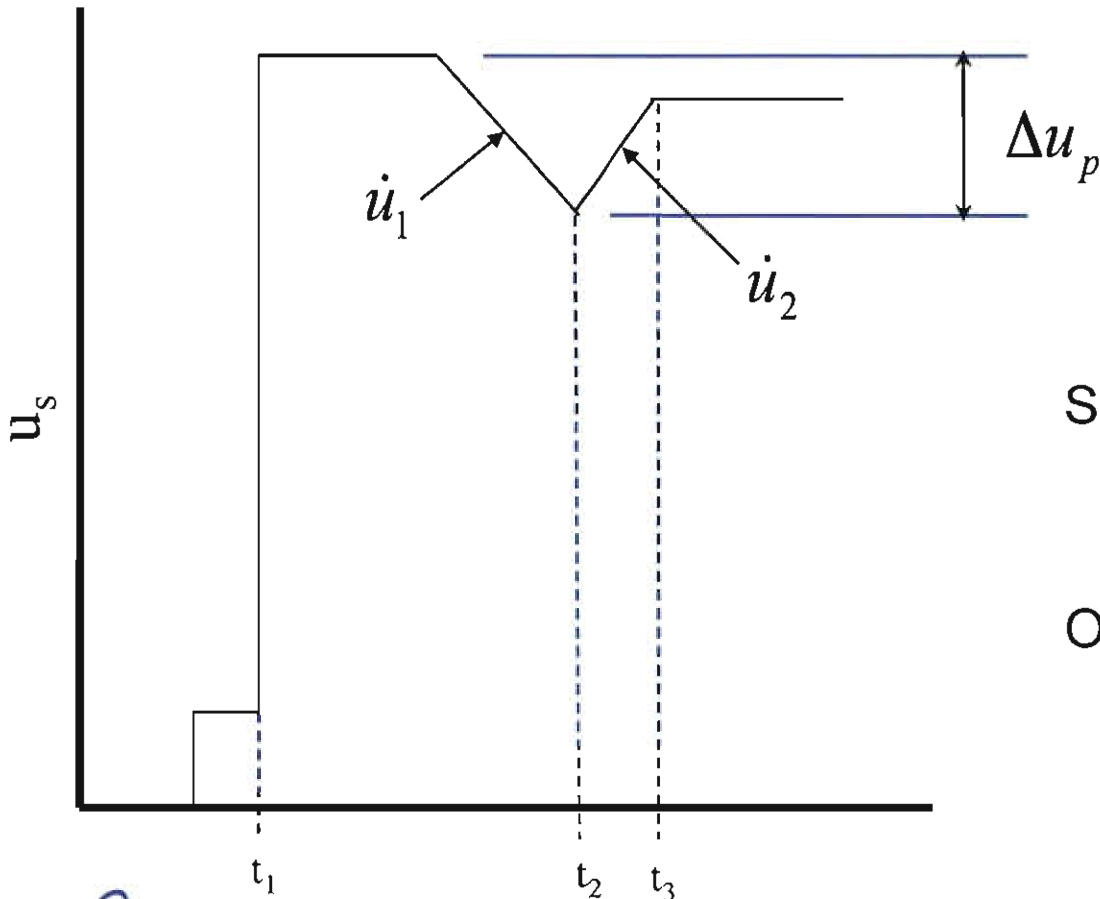
(a) (b) (c) (d)

Fig. 2 Microstructures tested: (a) 450 °C – 30 min (30 µm), (b) 600 °C – 1 hr (60 µm), (c) 850 °C – 1 hr (100 µm), (d) 900 °C – 35 min (200 µm).

Identical loading conditions yield similar VISAR results for 4 grain sizes.



Calculation of spall strength or onset stress from VISAR is dependent on the sound speed and change in particle velocity



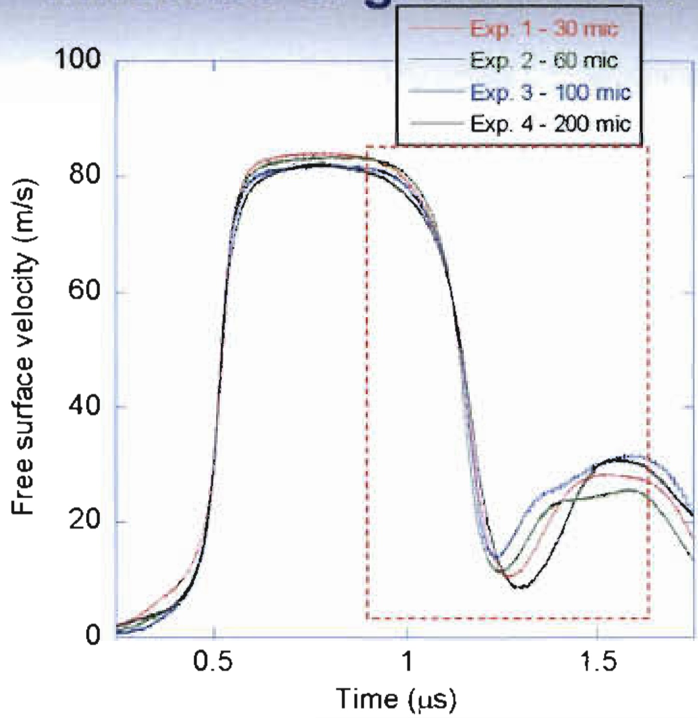
Spall strength:

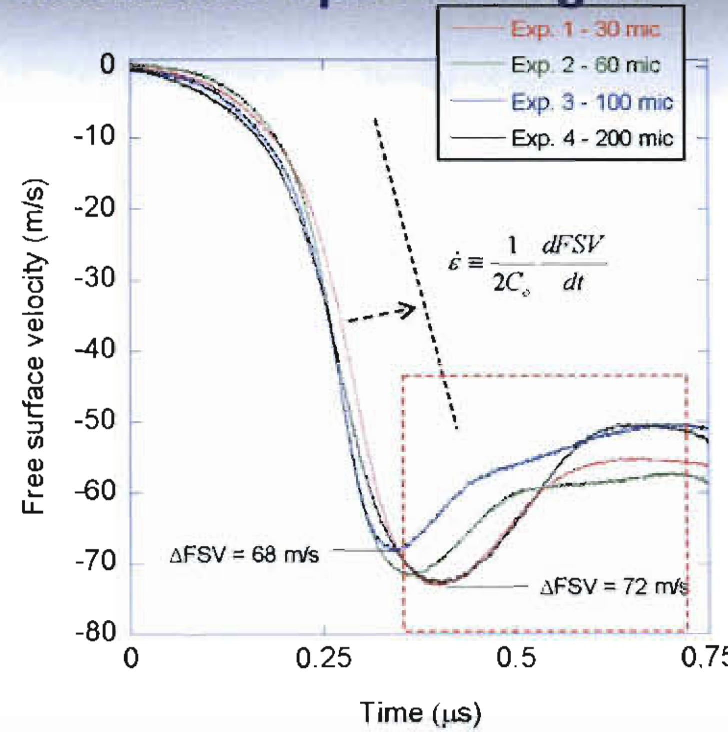
$$\sigma \approx \frac{1}{2} \rho_0 C_B \left(\Delta u_p + \delta \right)$$

Onset stress:

$$\sigma = \rho_0 C_L \Delta u_p \left(1 + \frac{C_L}{C_0} \right)^{-1}$$

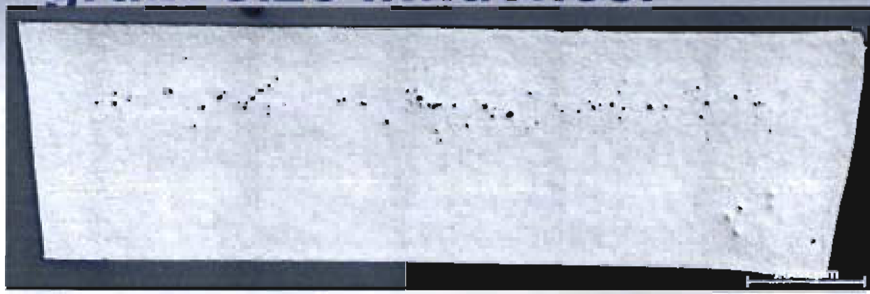
VISAR results from shock recovery experiments show very little influence of grain size on the calculated spall strength.

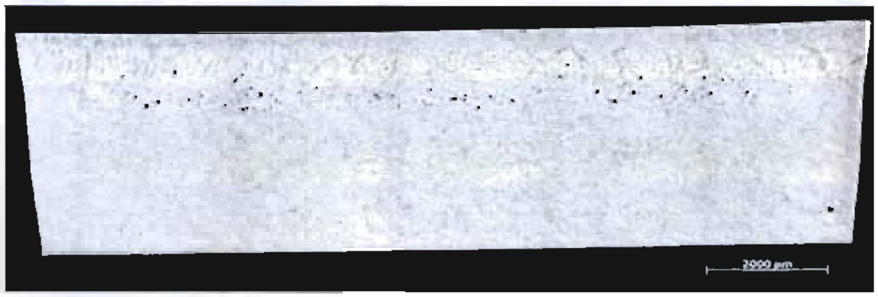


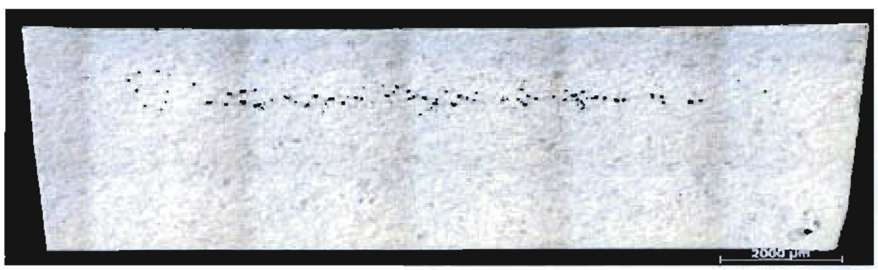


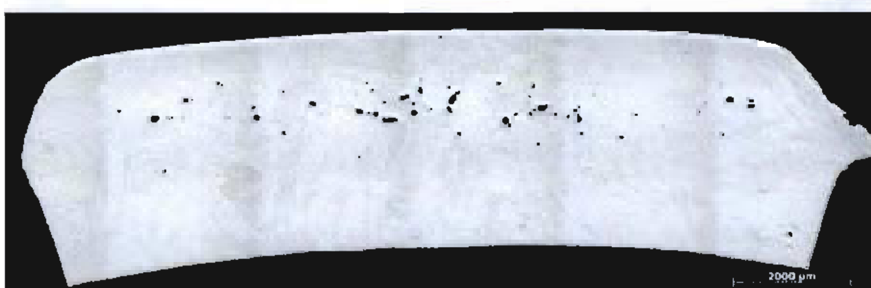
Experiment	Grain size	Impactor z-Quartz mm	Impact velocity (mm/us)	Target mm	Spall strength GPa
1s-1430	30 um	2.027	0.134	3.998	1.38
1s-1440	60 um	2.027	0.133	4.030	1.36
1s-1476	100 um	2.056	0.138	4.034	1.31
1s-1434	200 um	2.025	0.131	3.899	1.38

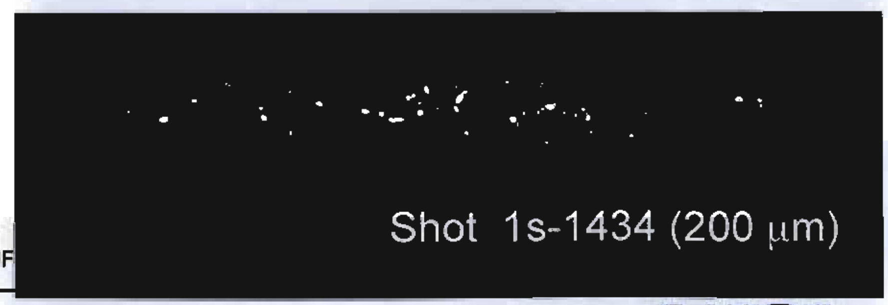
2D optical cross sections reveal differences due to grain size influence.

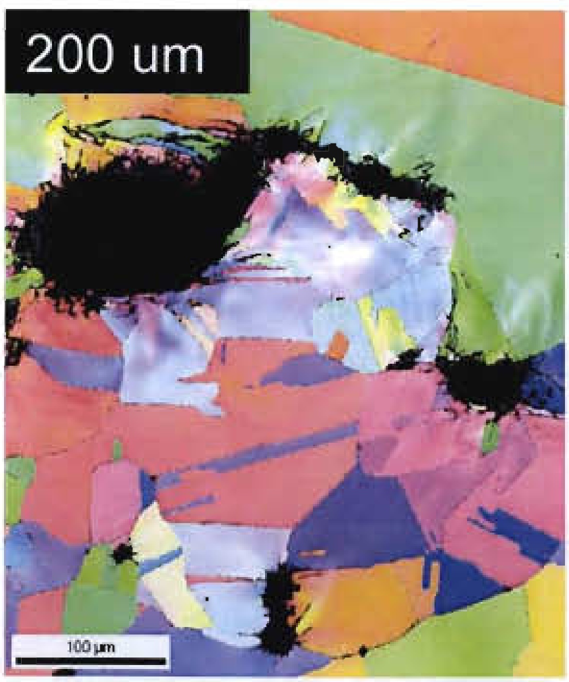








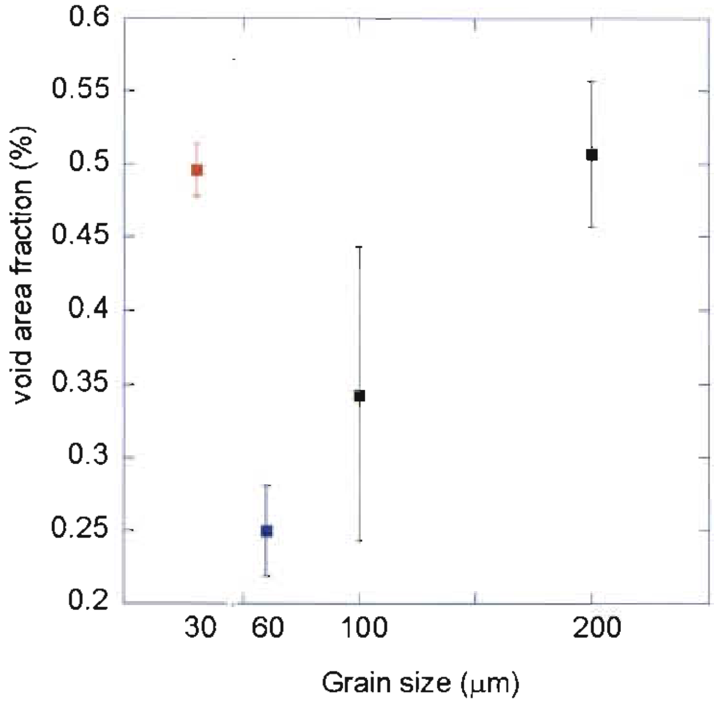


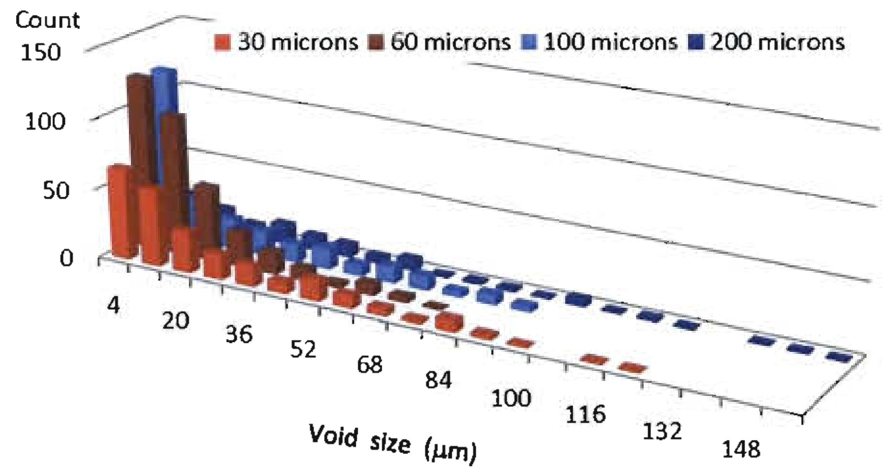


Damage Statistics from 2D optical analysis

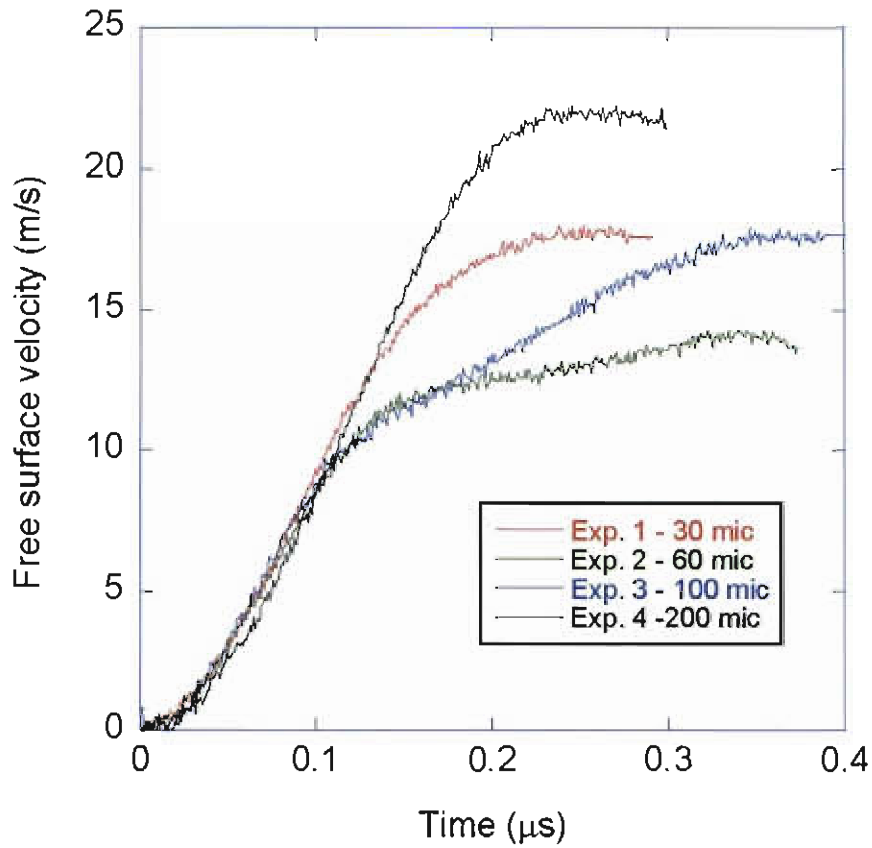
Experiment	Grain size	Number of voids	Void area fraction (%)	Avg Void diameter (um)
1s-1430	30 um	236	0.496	38.1
1s-1440	60 um	343	0.249	22.7
1s-1476	100 um	267	0.416	33.0
1s-1434	200 um	111	0.507	55.1

Void area fraction does not follow a linear trend.

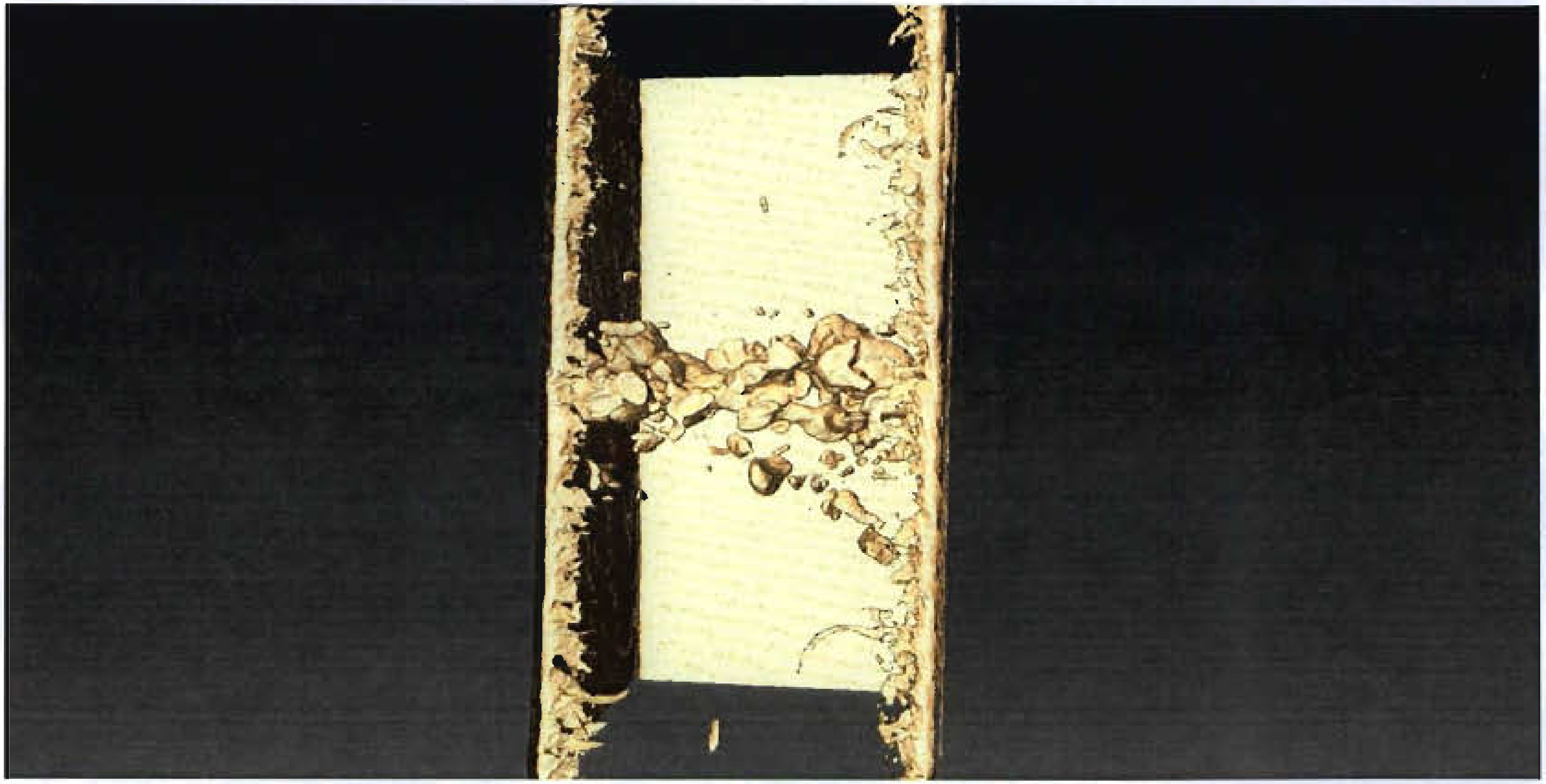




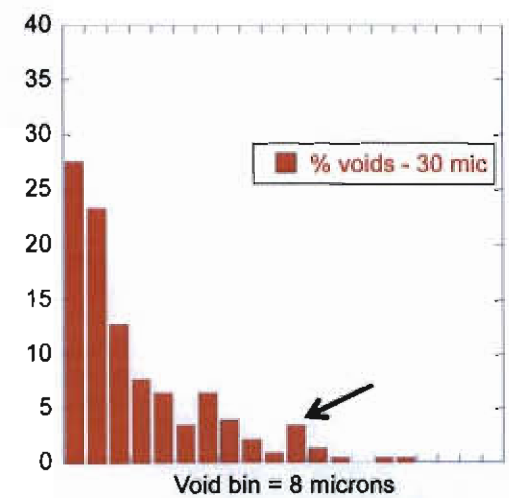
VISAR results show the difference between a slower rate growth process of individual voids and the faster process of coalescence.



3D microtomography is providing new insight into dynamic material response.

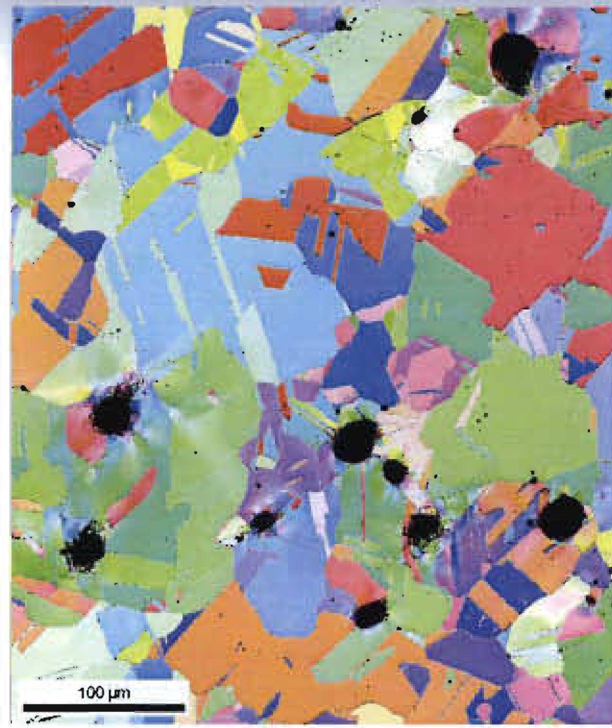


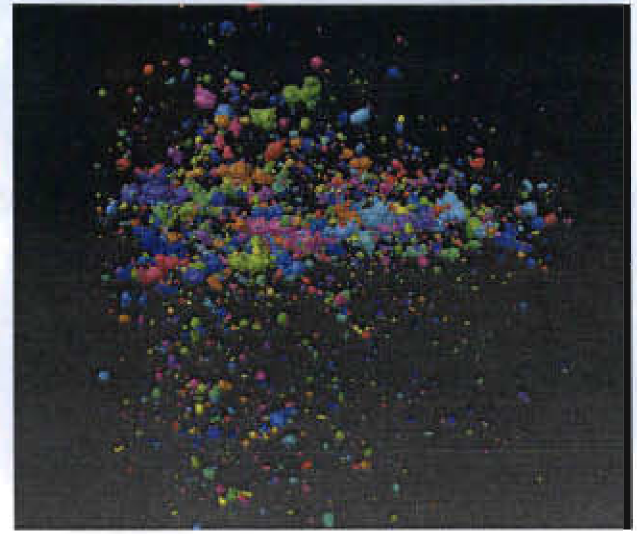
30 um samples have larger coalesced voids.

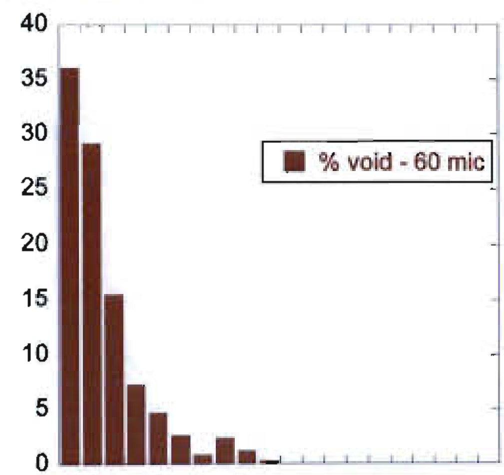


Both EBSD (2D) and tomography (3D) show larger voids. Arrows in OIM maps (and plot) show coalescence of small voids.

60 um samples have small isolated voids that do not indicate significant coalescence.



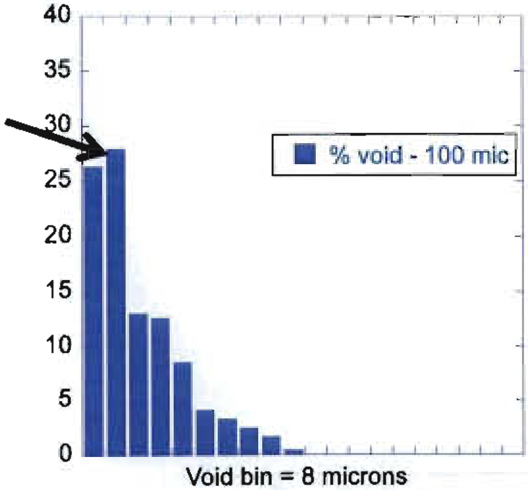




Void bin = 8 microns

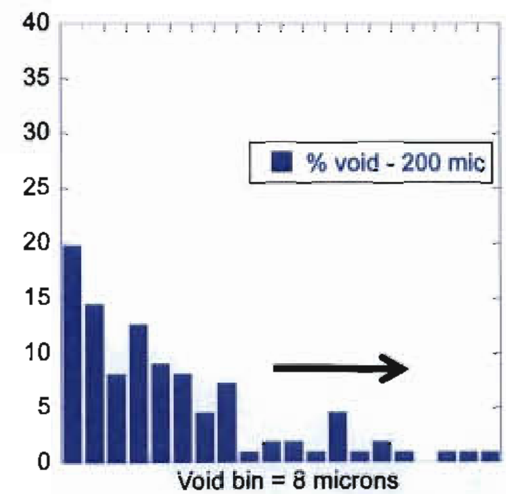
Both EBSD (2D) and tomography (3D) show smaller and isolated voids as compared with the 30 µm case.

In the 100 um case some voids have grown, but voids largely remain isolated.



EBSD (2D) isolated voids (as 60 µm) but some started to grow. That is reflected on the plot showing the void distribution (arrow).

In the 200 um case, voids have grown and coalesced and damage is well developed.



Both EBSD (2D) and tomography (3D) show the largest voids, also reflected on the distribution plot (arrow).

A critical length scale is necessary for the transition from individual void growth to void coalescence.

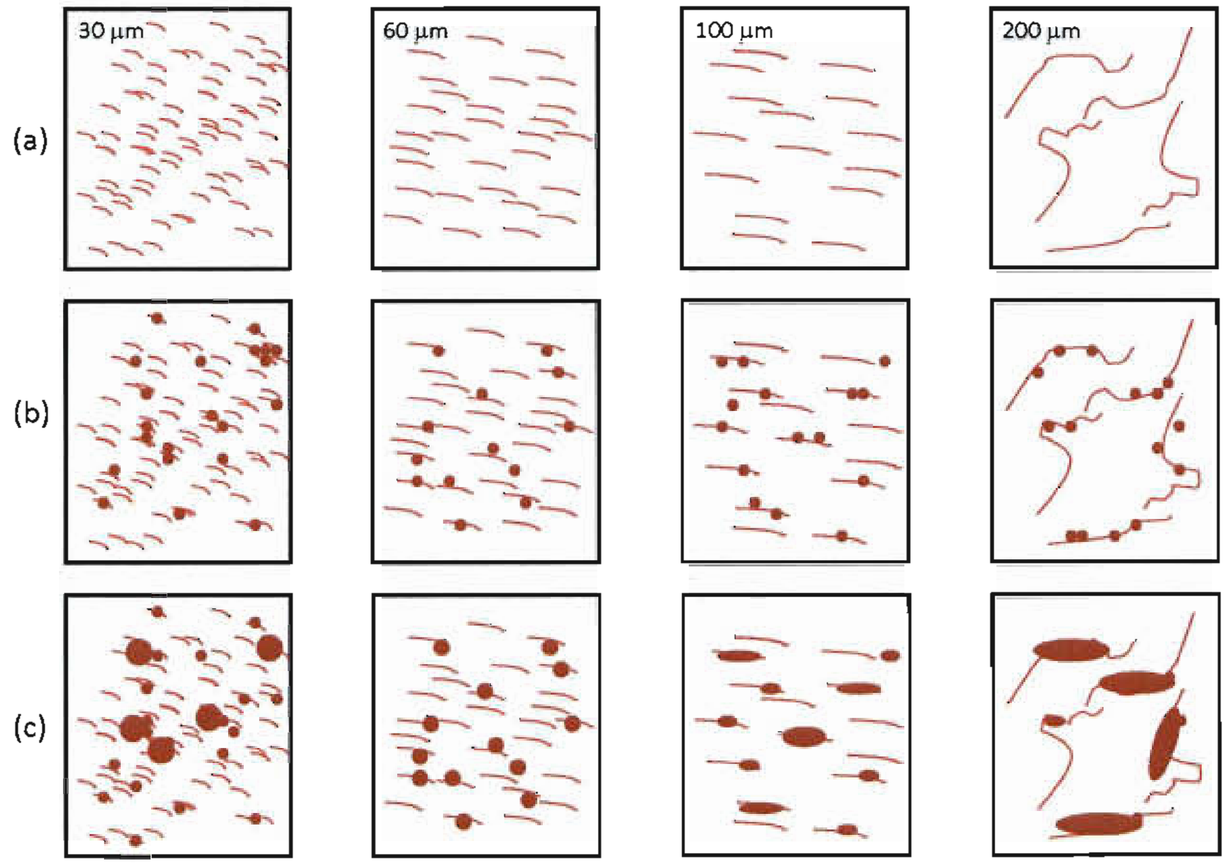
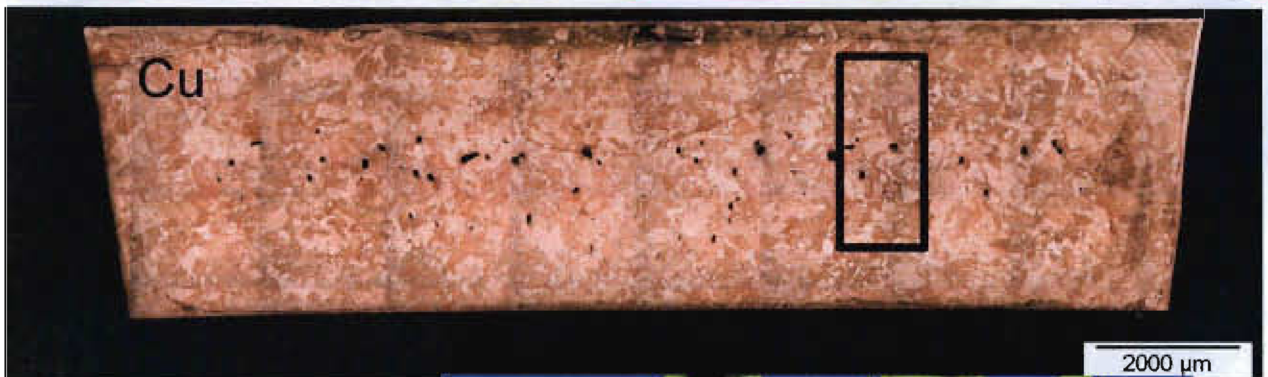
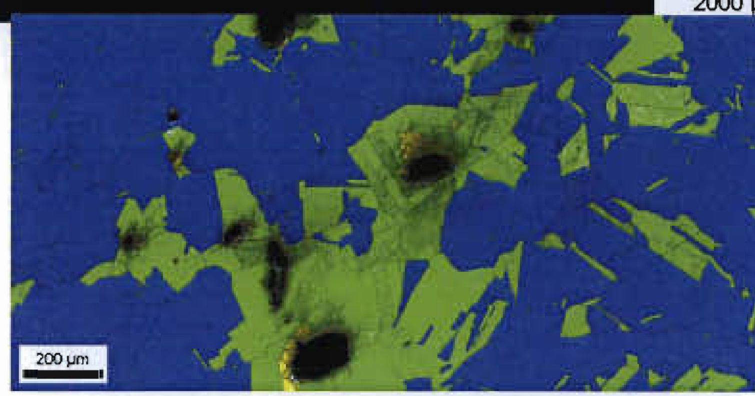


Fig. 13 Mechanisms proposed: (a) initial configuration of the grain boundaries ≠ Σ3. (b) microstructure during void nucleation stage, (c) resultant microstructure after void growth + coalescence

What are the mechanisms controlling coalescence of voids?



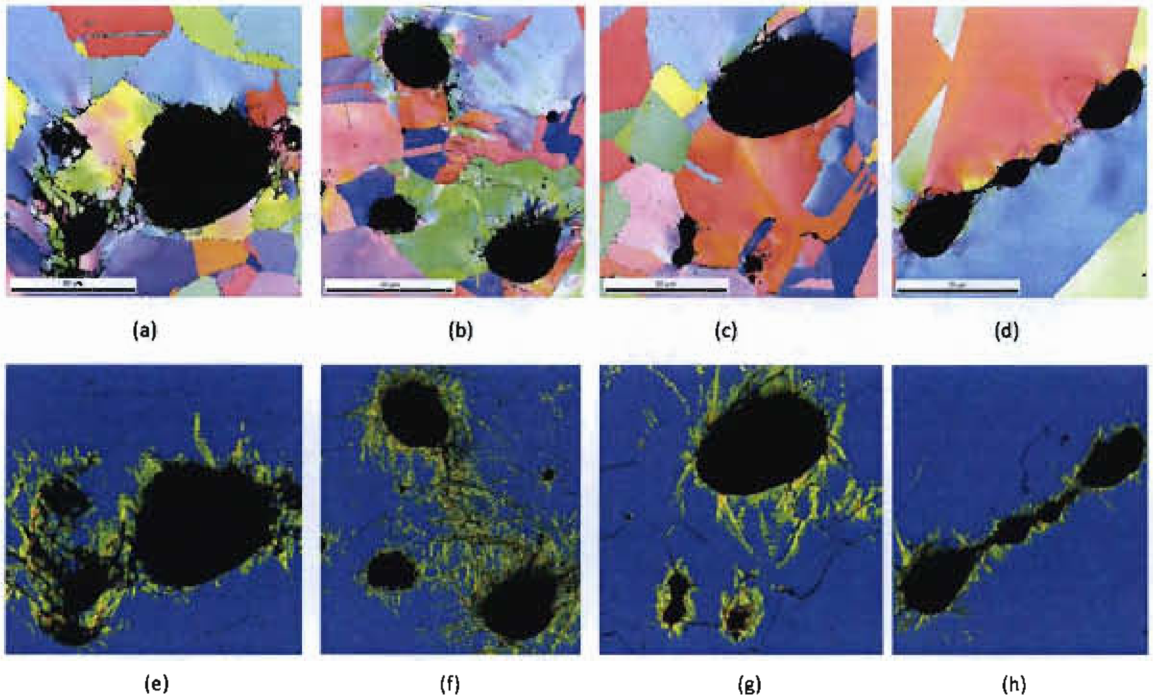


	Min	Max	Total Fraction	Partition Fraction
Blue	0	0.6	0.971	0.971
Green	0.6	1.7	0.026	0.026
Yellow	1.7	4	0.000	0.000
Orange	4	8	0.000	0.000
Red	8	16	0.000	0.000

Boundaries: <none>

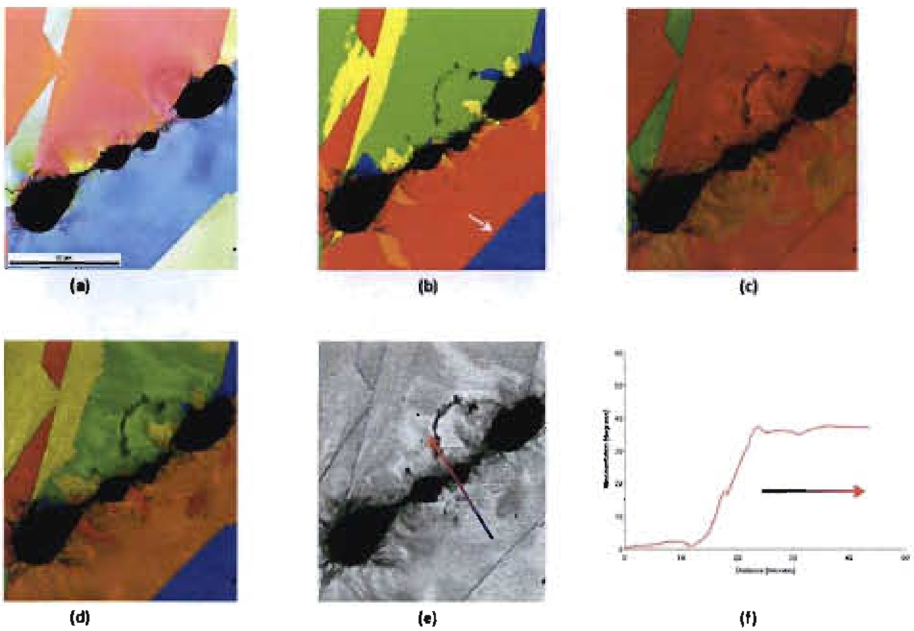
Regions of enhanced misorientation may lead to damage coalescence

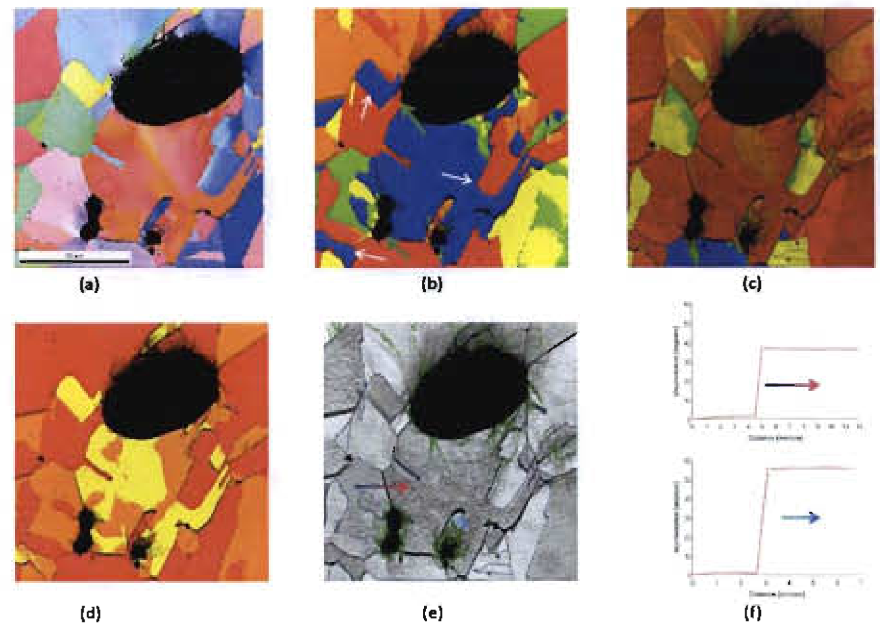
Average kernel misorientation relates plastic deformation to microstructural misorientation



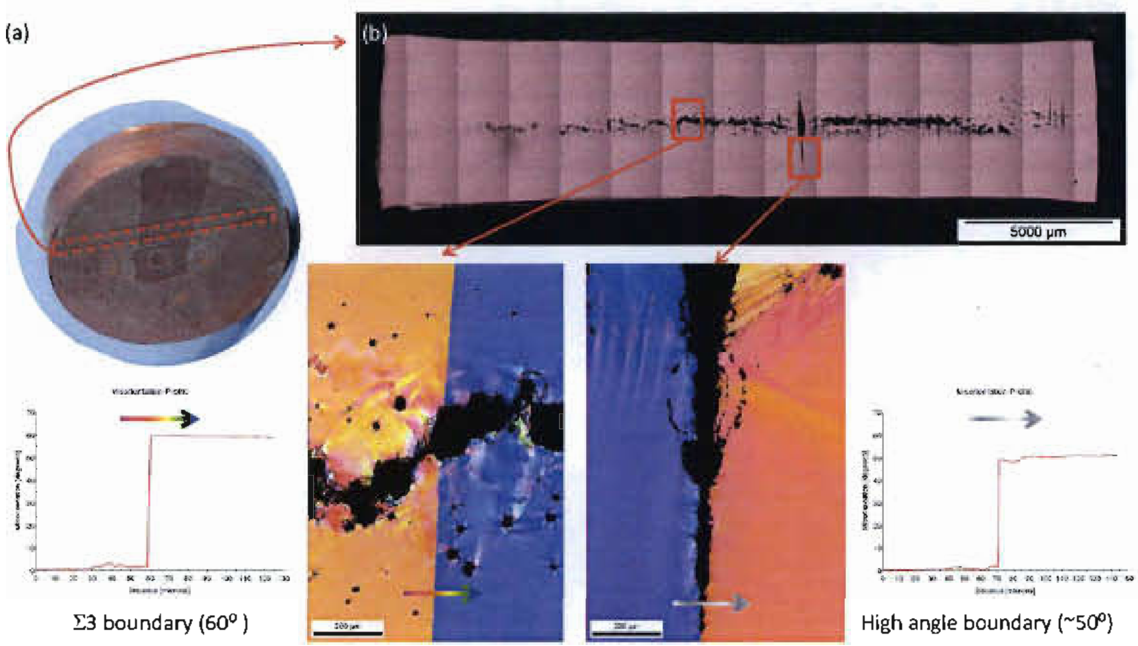
- Coalescing voids show highly localized regions of misorientation
- Individually growing voids show overlapping regions of misorientation which may indicate the pathway for coalescence to begin.

Taylor/Schmid factor and elastic stiffness show no clear changes with respect to damage location.





Grain boundary type does seem to have an influence.



- Low angle boundaries Σ1 (<5°) show no void formation
- High angle boundaries Σ3 (60°) show no void formation
- All voids form at boundaries between 15° and 55°

Summary

- Los Alamos is an exciting place to work!
- Shock loading and microstructure are intimately connected to yield a dynamic material response.
- A critical length scale exists where mechanisms of ductile damage formation transition from growth to coalescence dominated.
- An understanding of mechanisms dominating damage regimes is necessary to in quantitatively interpret velocimetry results.
- Voids are preferentially nucleated at grain boundaries between 15°-55°
- Plastic work observed in the microstructure indicates that the stress evolution plays a critical role in the resultant damage.