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

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Los Alamos NATIONAL LABORATORY
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Controlled Shock Loading for Microstructural Correlation of Dynamic Damage Behavior

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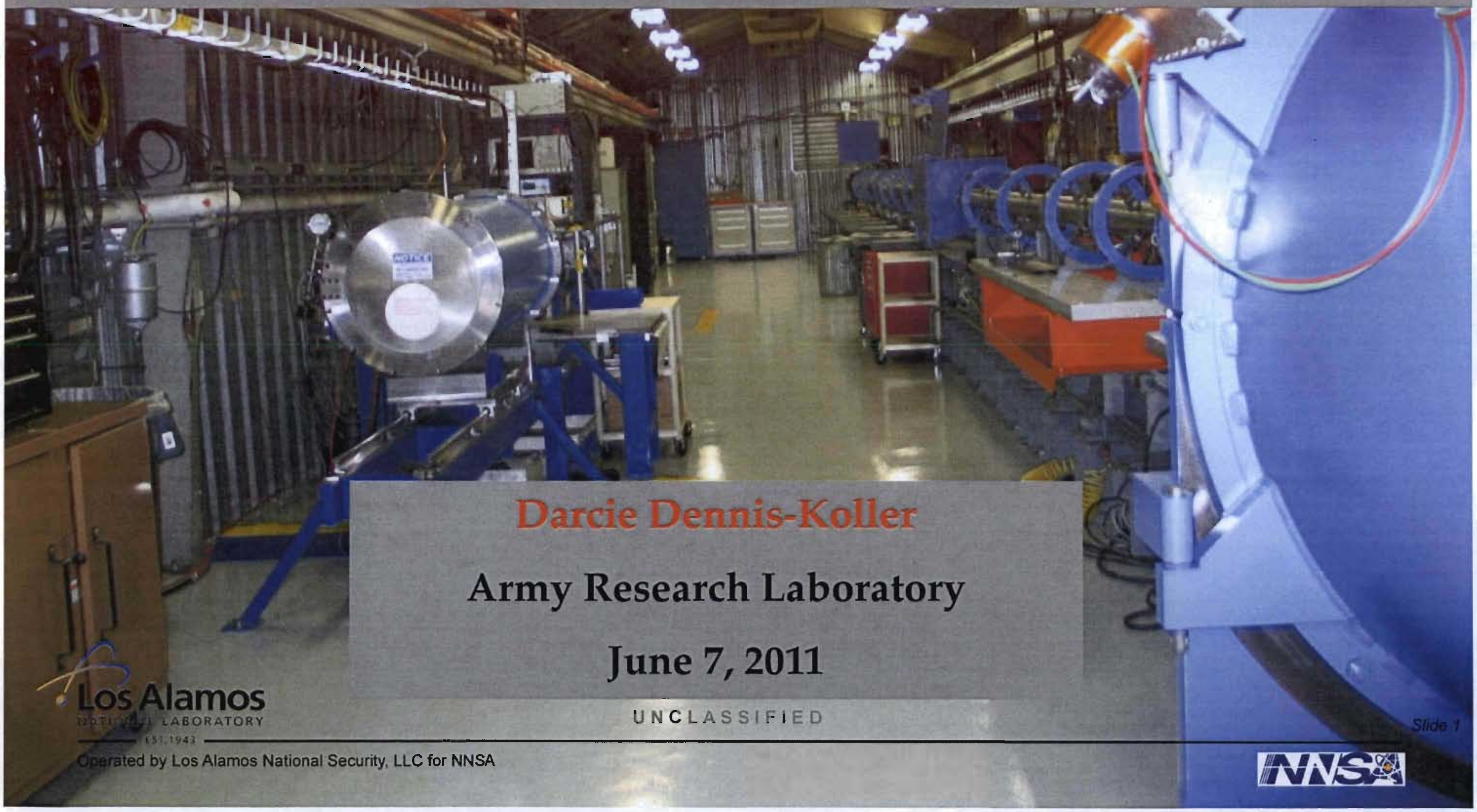
Materials performance is recognized as being central to many emergent technologies. Future technologies will place increasing demands on materials performance with respect to extremes in stress, strain, temperature, and pressure. In this study, the dynamic ductile damage evolution of OFHC Cu is explored 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 $\sum 1$ and high angle $\sum 3$) proved to be resistant to void nucleation. Based on these findings, mechanisms for the void nucleation/growth and coalescence are proposed.

Controlled Shock Loading for Microstructural Correlation of Dynamic Damage Behavior



Darcie Dennis-Koller

Army Research Laboratory

June 7, 2011

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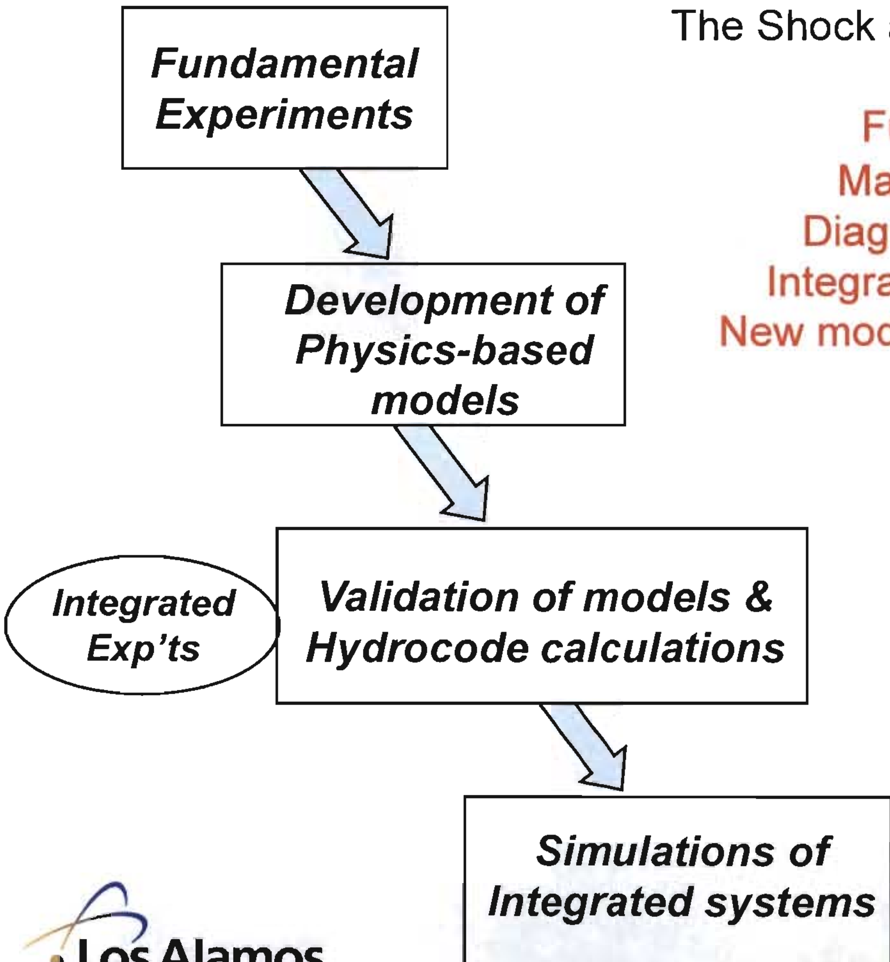
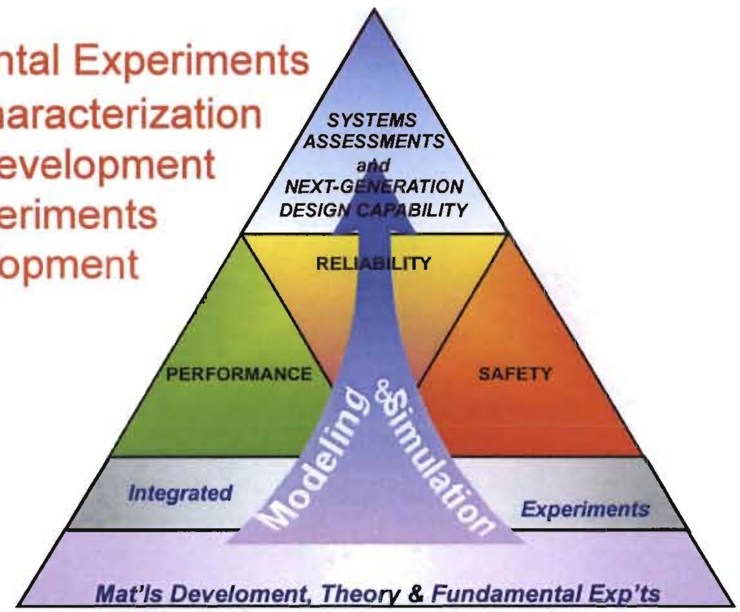
Experimental activities in Shock and Detonation Physics at Los Alamos enable realistic simulations of material systems.



The Shock and Detonation Physics Group is involved in:

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

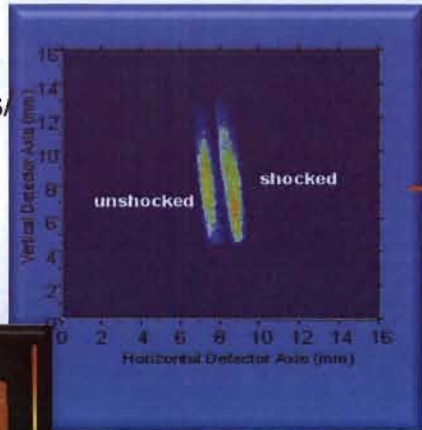


Underlying Research theme is "Materials Properties under Extreme Conditions"

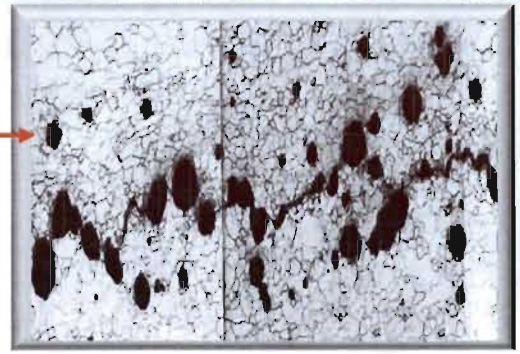
Pressure, Temperature, Strain Rate, Chemistry

Shock physics experiments are essential to fundamental scientific materials studies.

Micro-scale –
Atomistic Calculations/
Dynamic XRD



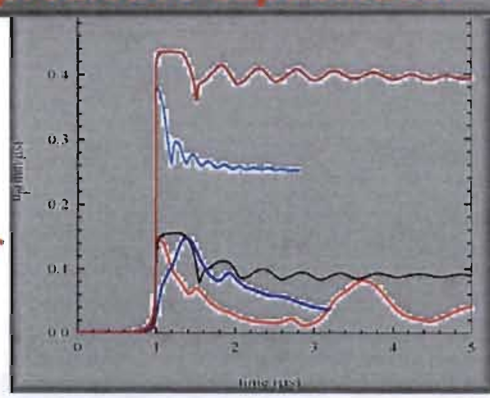
Meso-scale – Shock Recovery



Continuum scale –
VISAR/Gas Gun
Experiments

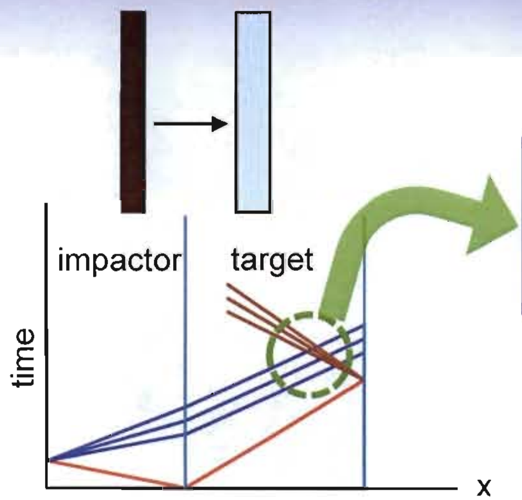
This work ultimately supports our fundamental understanding of materials by enabling high-fidelity predictive capabilities.

Data



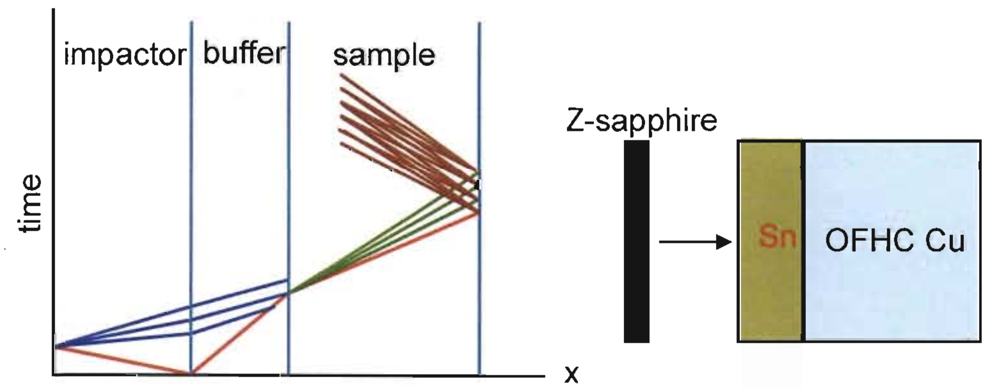
Physics models in large scale computer simulations

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



Flat top spall experiment

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.



Triangle wave spall experiment

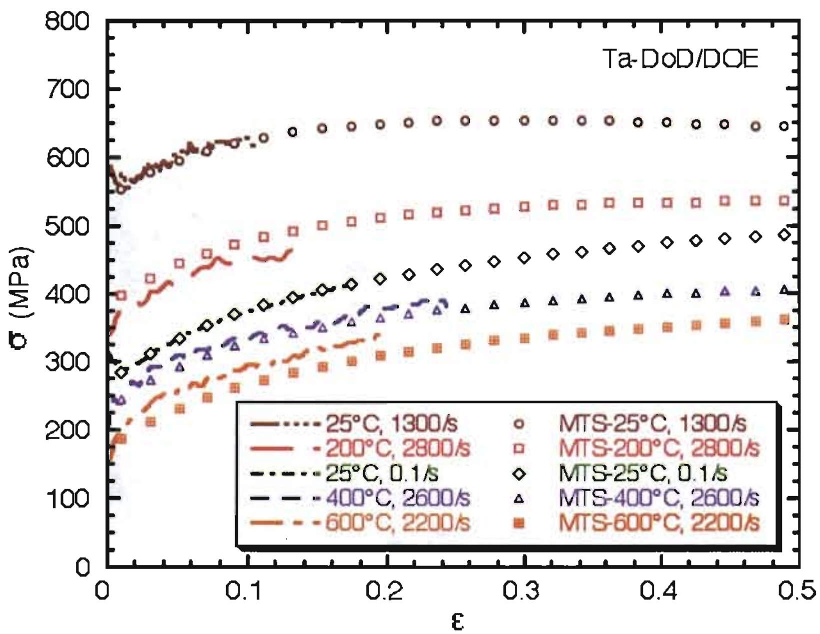
- HE loading has triangular wave shape (Taylor wave)
- Duration of release in plate impact experiment differs from that of a real Taylor wave; much shorter in the gun
- Accomplished through an overtake experiment using a Tin buffer

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

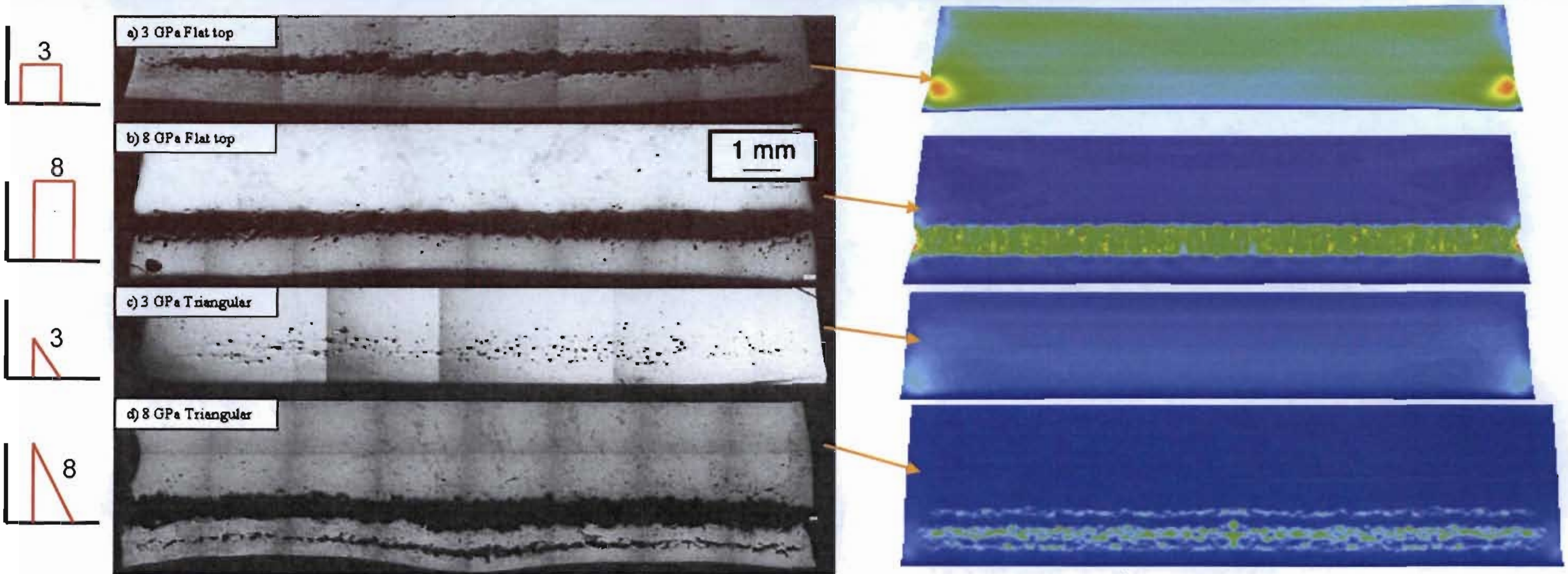
Typical Materials Characterization is at Low or Moderate Strain Rates



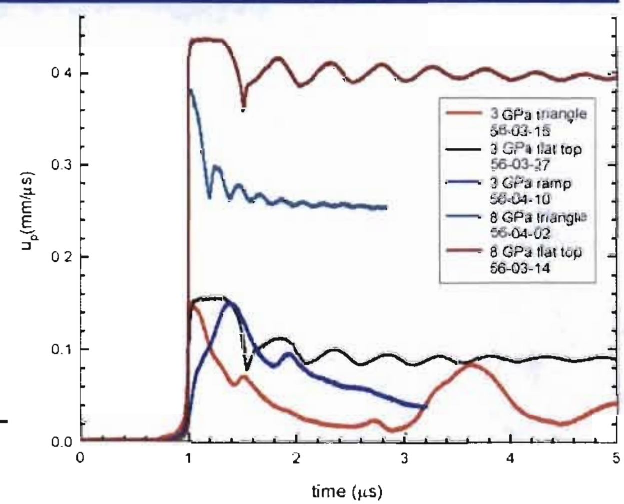
S.R. Chen and G.T. Gray III, Metall. & Matls. Trans., vol. 27A, (1996), pp. 2994-3006."Constitutive Behavior of Tantalum and Tantalum-Tungsten Alloys"

- 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



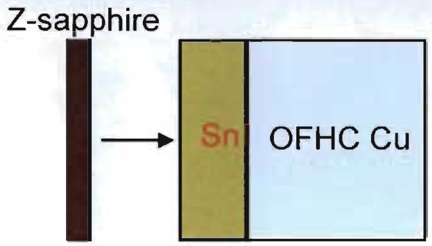
These simulations illustrate current damage model capabilities

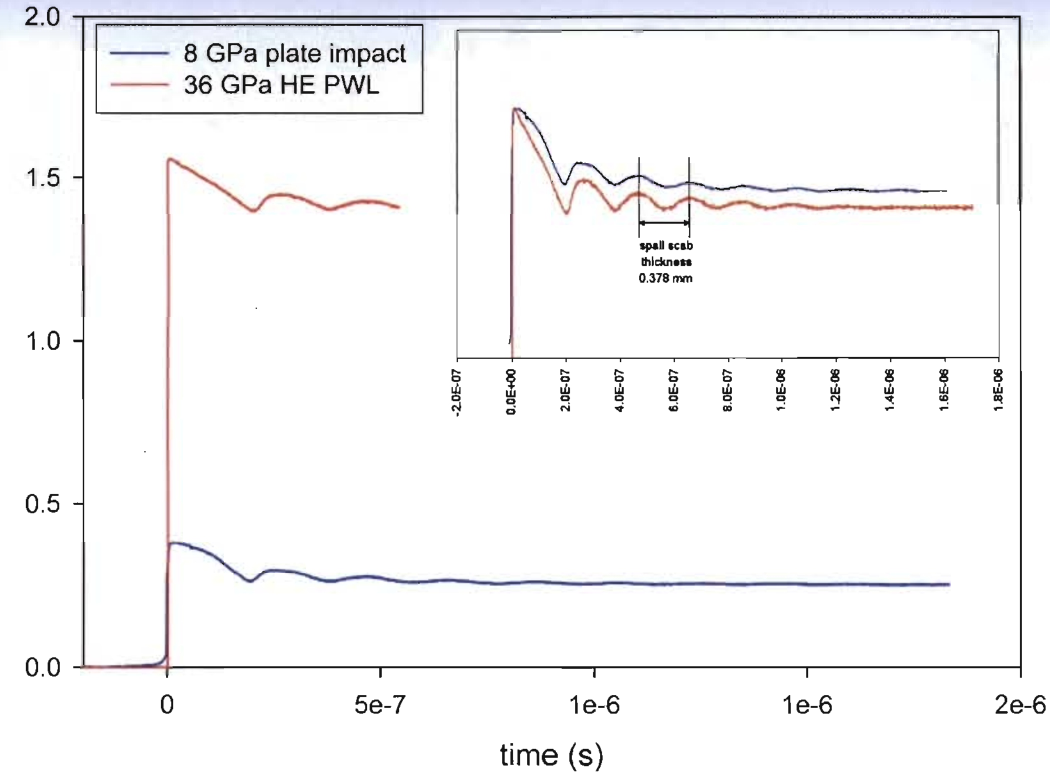


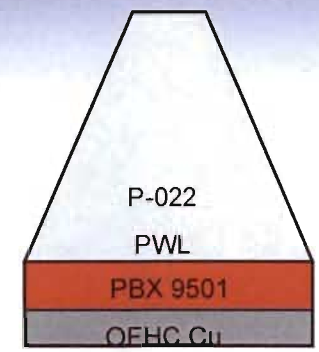
Koller and Cerreta, *J. Appl. Phys*, Nov. 2003

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

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

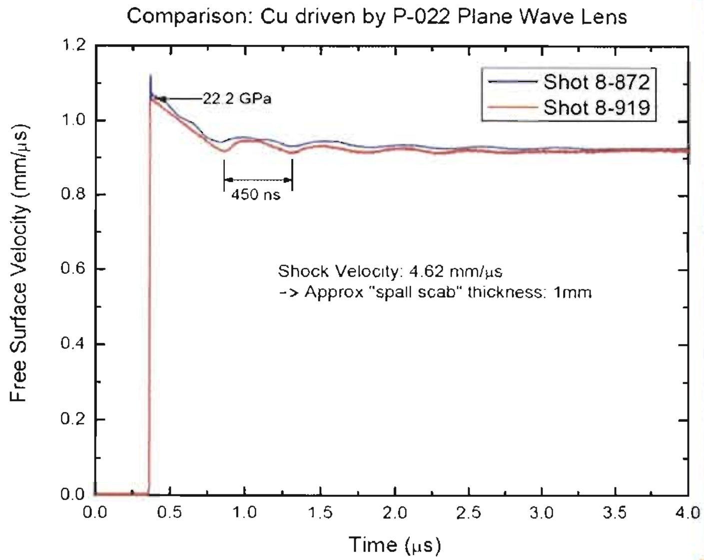






- Experiment shows that plate impact experiments can be used to explore a range of peak pressure states while maintaining the same strain rate on the release.
- When the 9501 booster was added the duration of the tensile pulse was shortened and the material spalled just as was seen in the plate impact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

Under High Explosive Loading our Previous Understanding was Not Validated

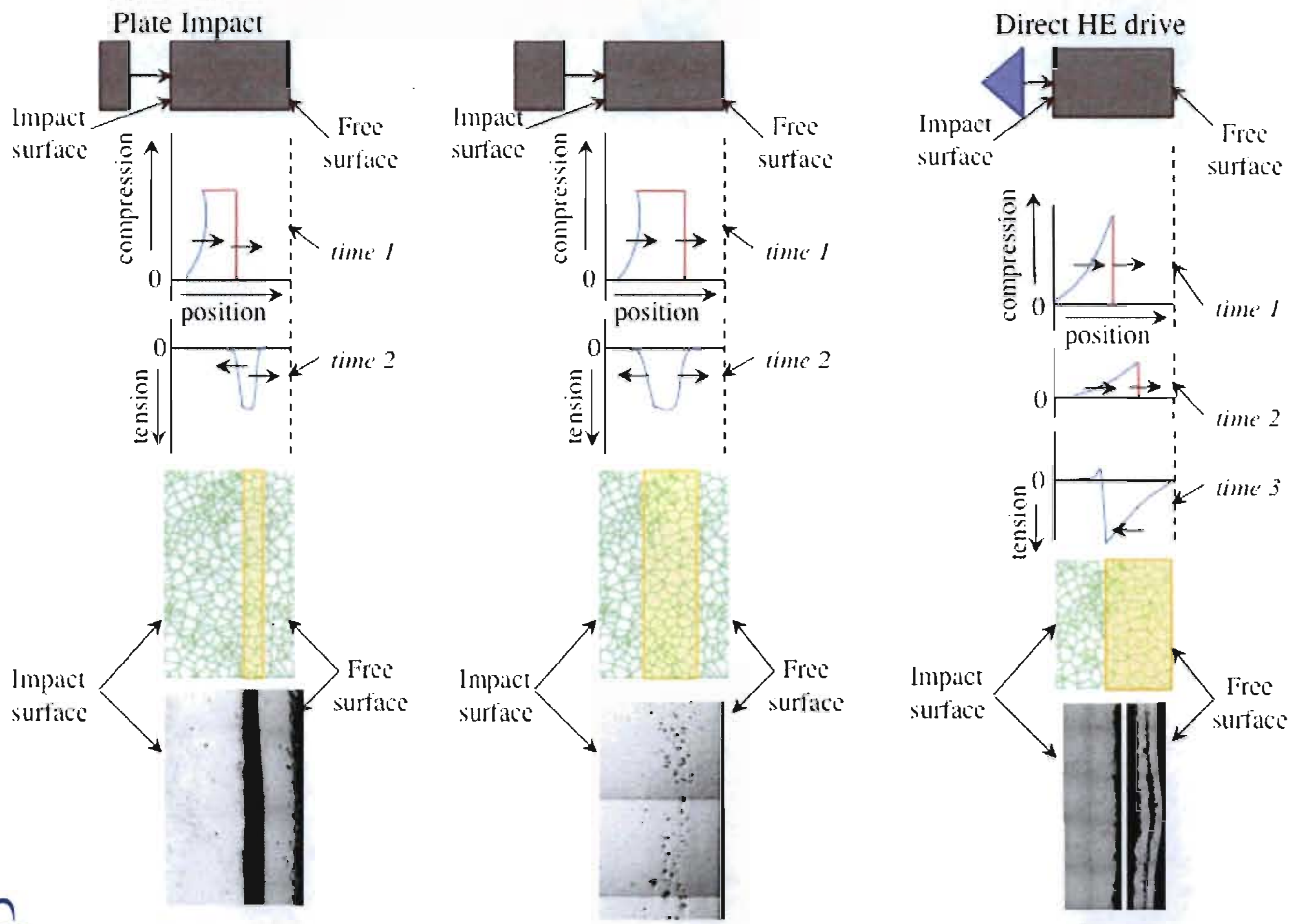


Peak Pressure = 22GPa
Direct HE

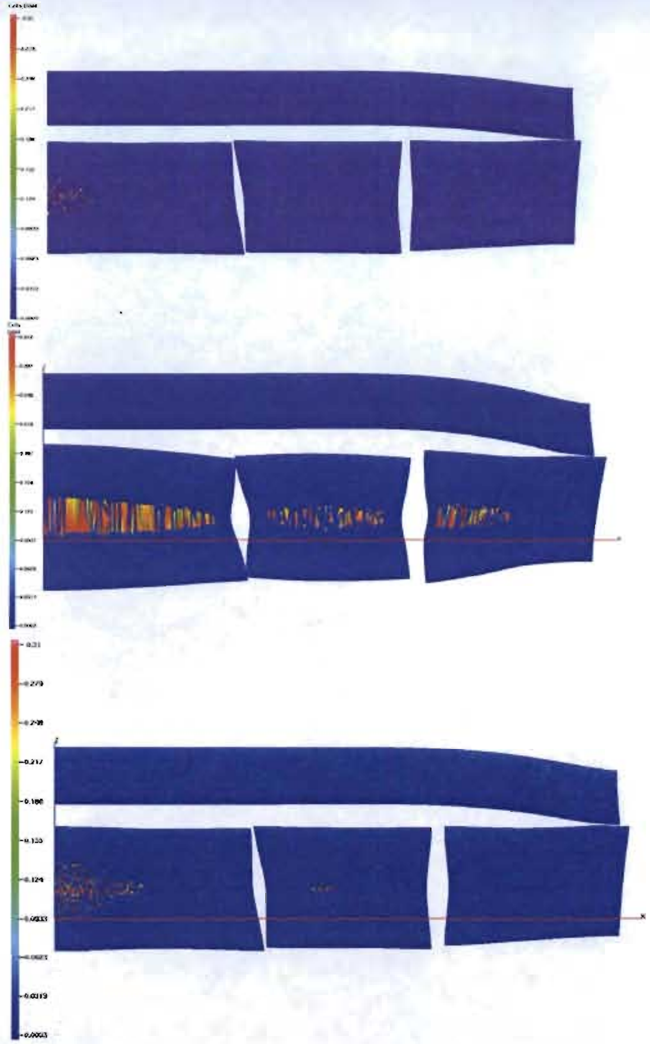
Koller and Cerreta, *APS SCCM Proceedings*, 2005.

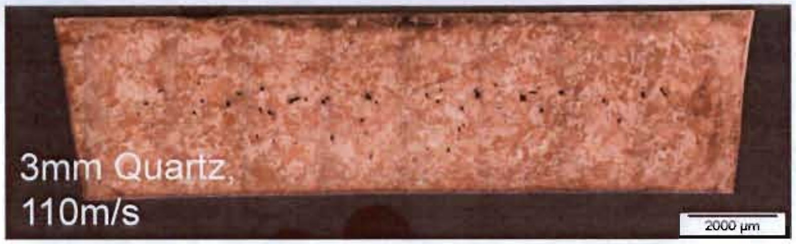
Hypothesis: kinetic and spatial parameters have an important role in dynamic damage evolution

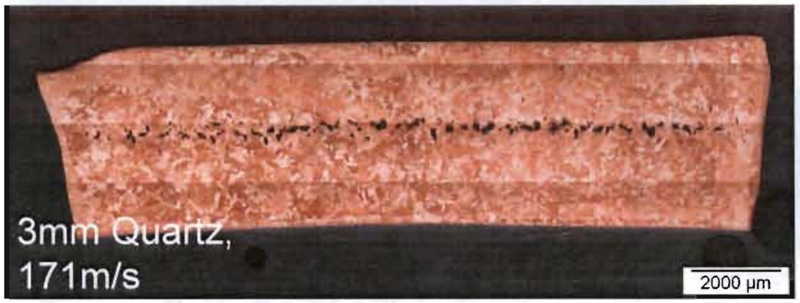
Changes in shock wave shape result in changes in the evolution of the stress profile applied to the microstructure.



Scoping Calculations and Determination of Early Stage Damage







Well characterized starting materials are a critical component for shock recovery experiments.

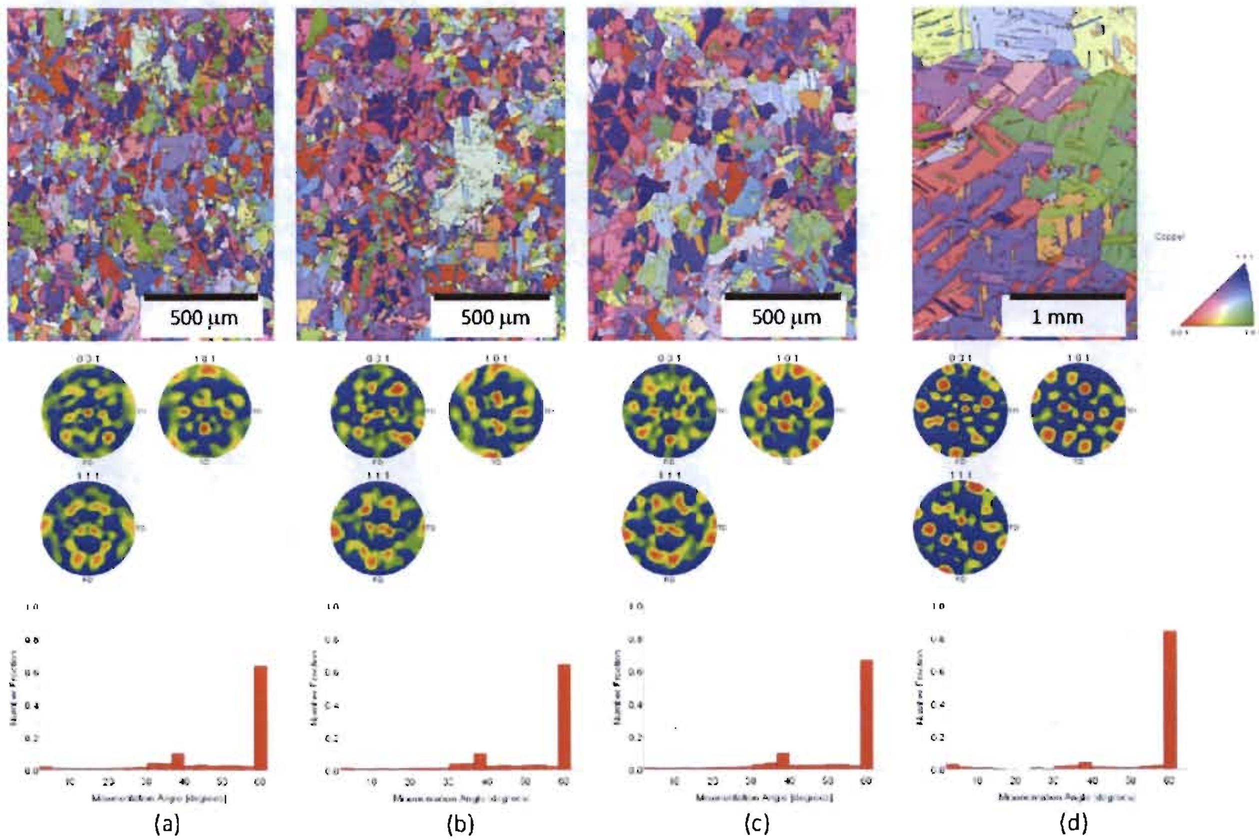
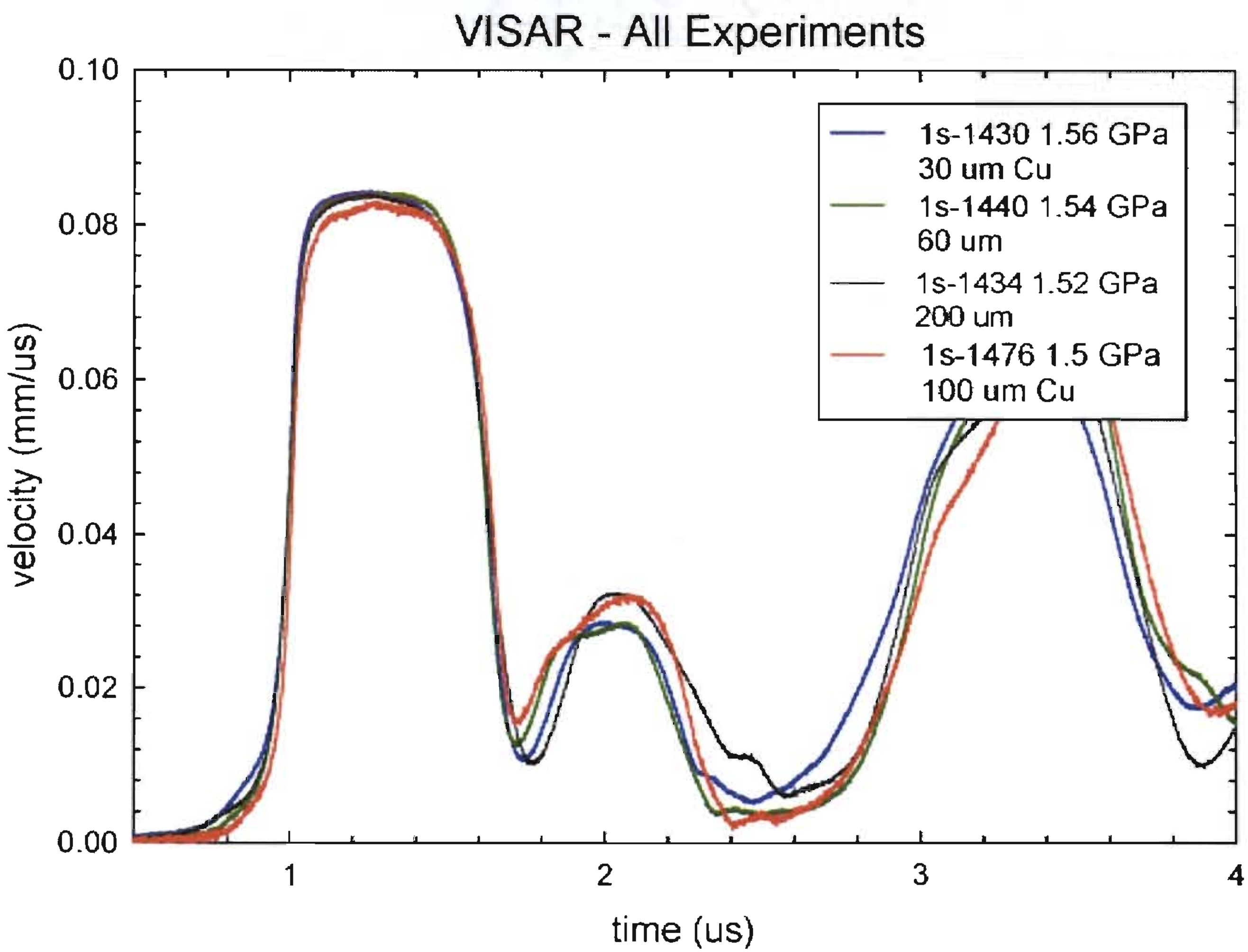
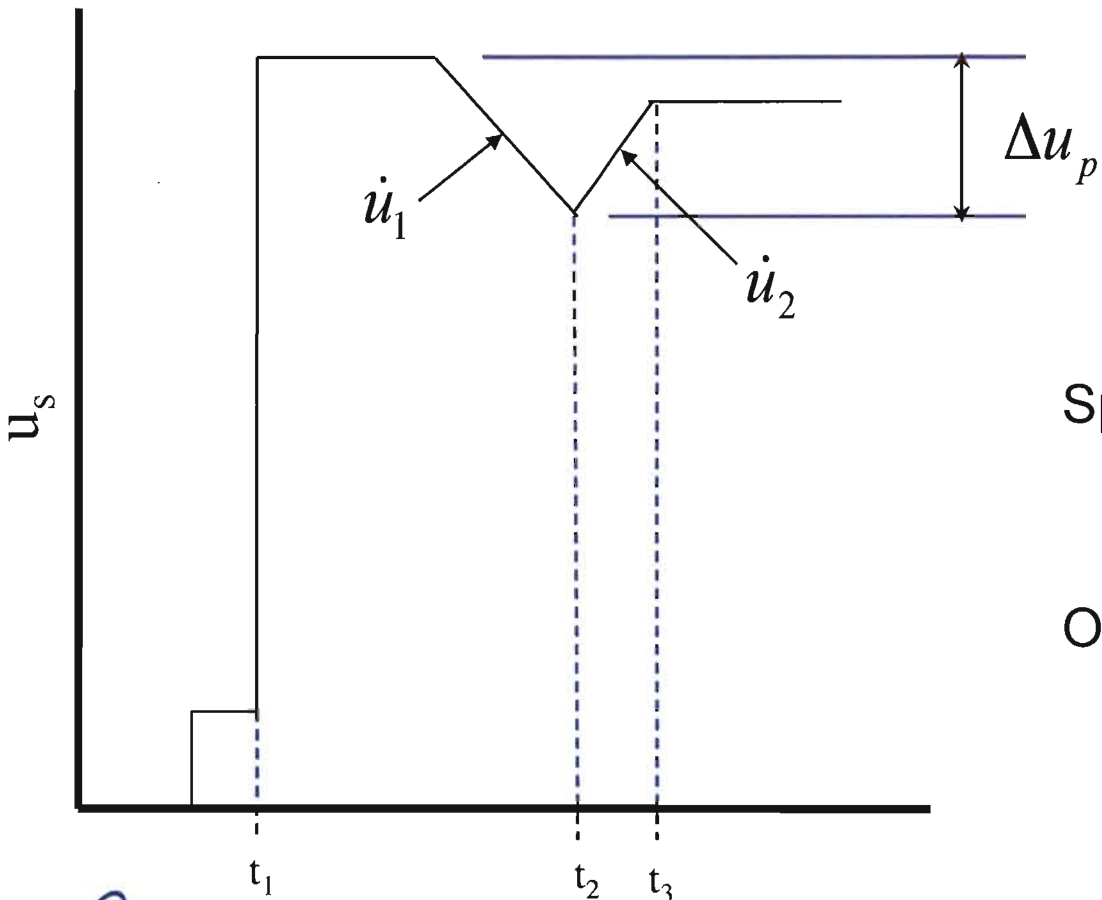


Fig. 2 Microstructures tested: (a) 450 °C – 30 min (30 μm), (b) 600 °C – 1 hr (60 μm), (c) 850 °C – 1 hr (100 μm), (d) 900 °C – 35 min (200 μm).

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



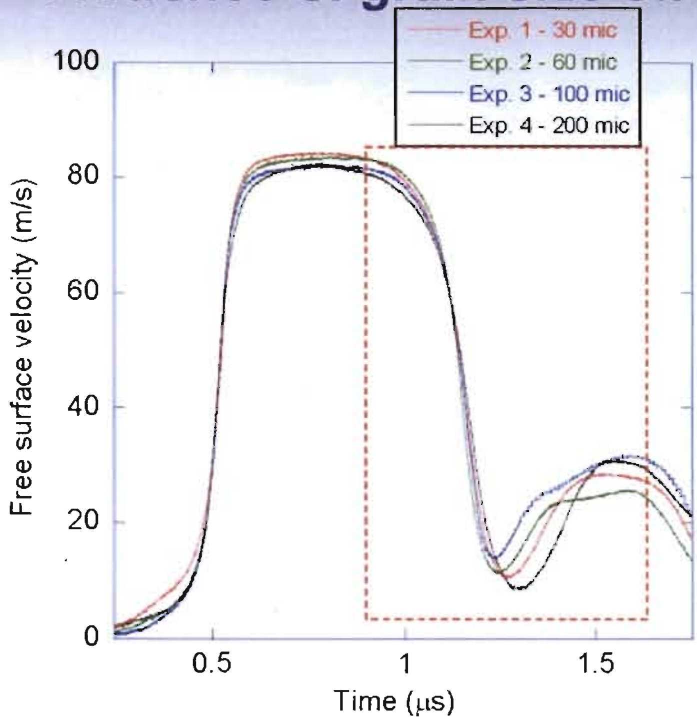
Spall strength:

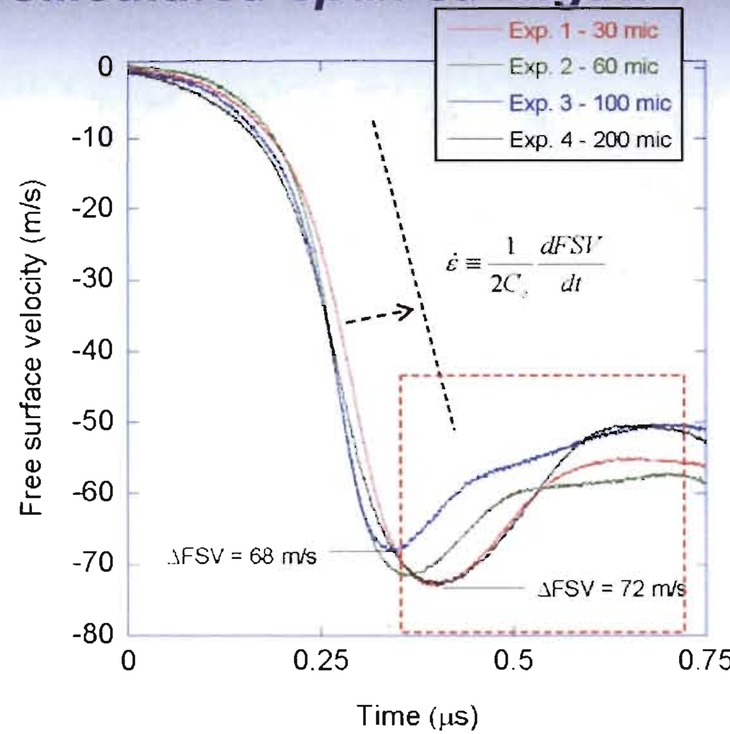
$$\sigma \approx \frac{1}{2}\rho_0 C_B \left(\Delta u_p + \delta\right)$$

Onset stress:

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

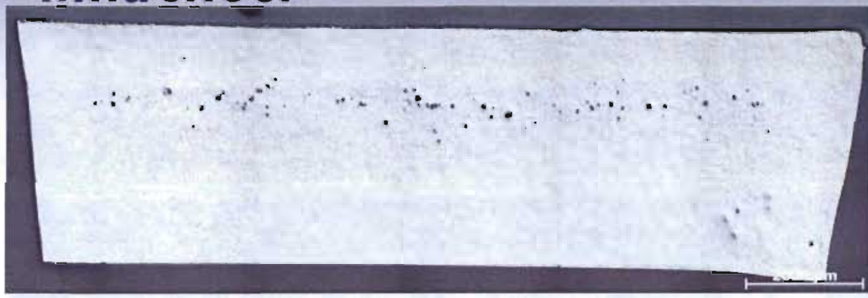
VISAR results from shock recovery experiments show very little influence of grain size on the calculated spall strength.

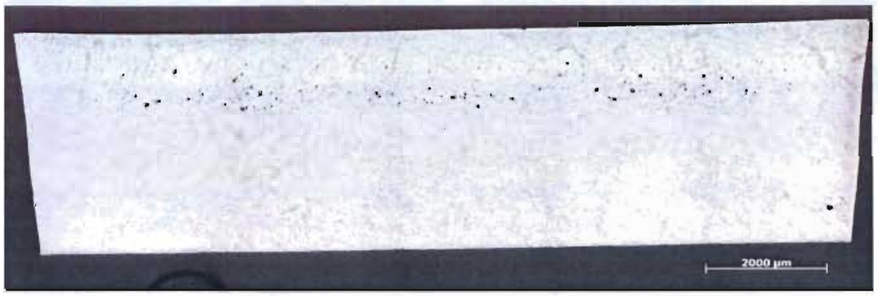


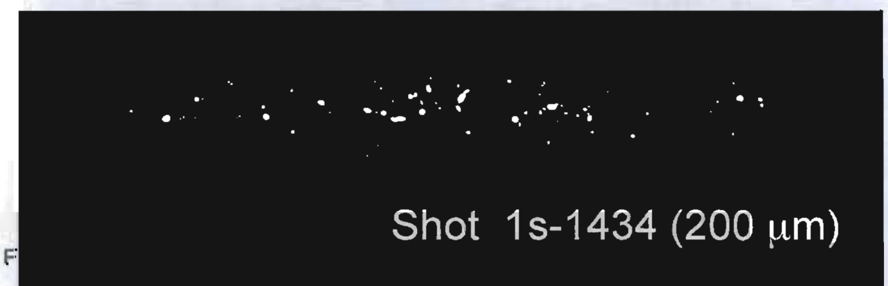


Experiment	Grain size	Impactor z-Quartz mm	Impact velocity (mm/us)	Target mm	Spall strength GPa
1s-1430	30 um	2.027	0.134	3.998	1.38
1s-1440	60 um	2.027	0.133	4.030	1.36
1s-1476	100 um	2.056	0.138	4.034	1.31
1s-1434	200 um	2.025	0.131	3.899	1.38

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







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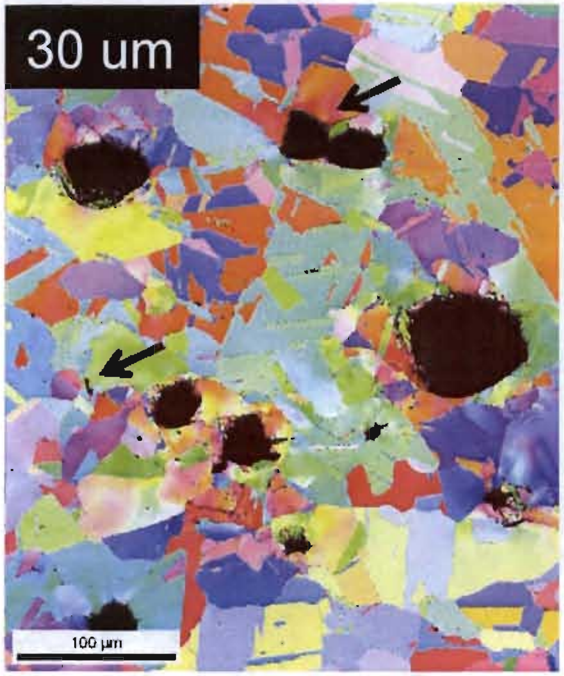
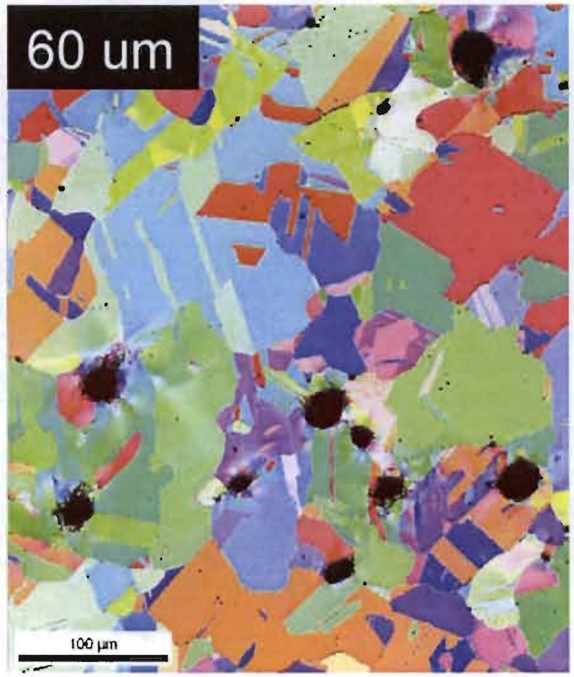
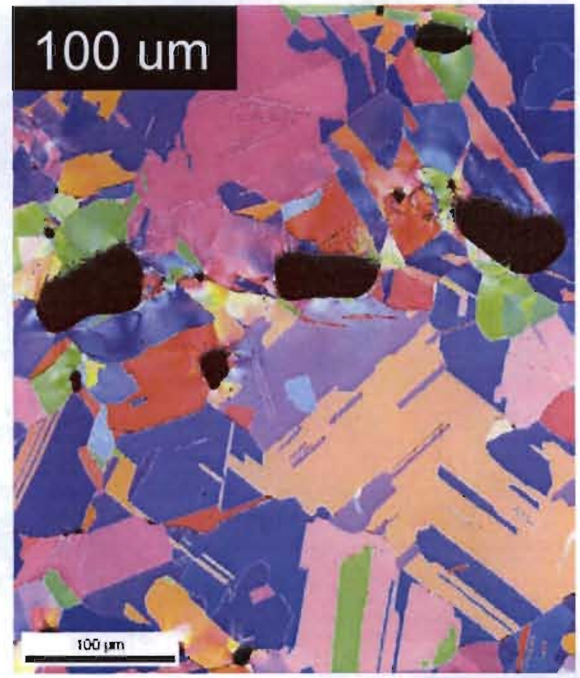
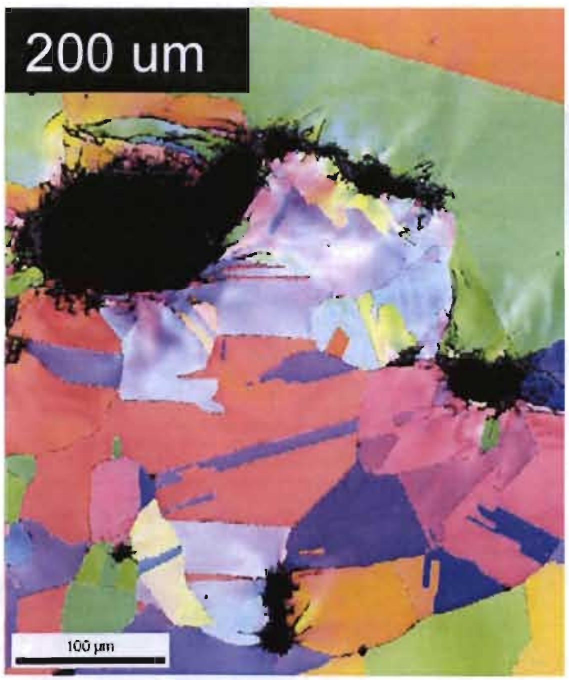




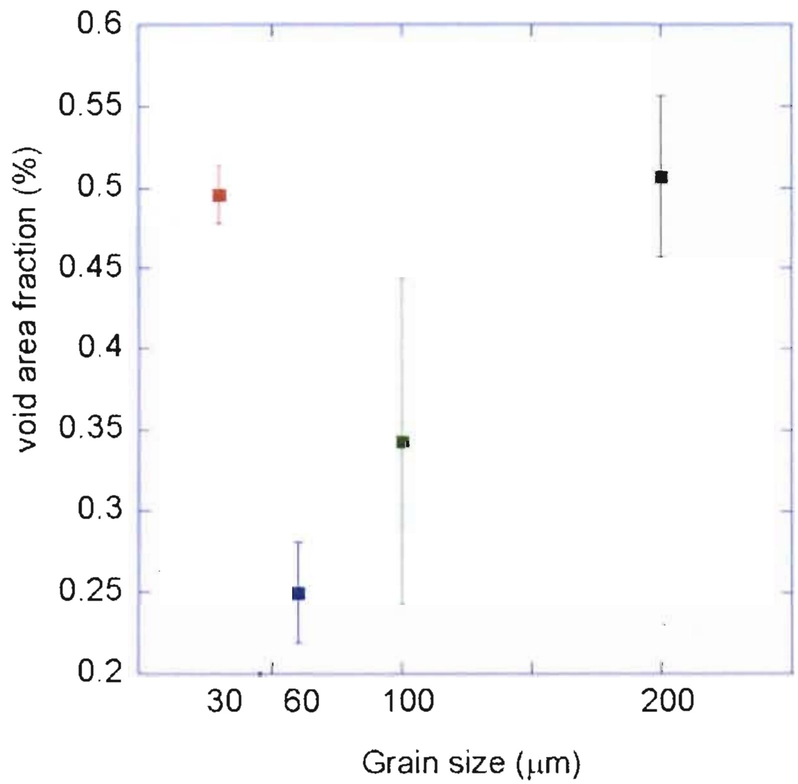


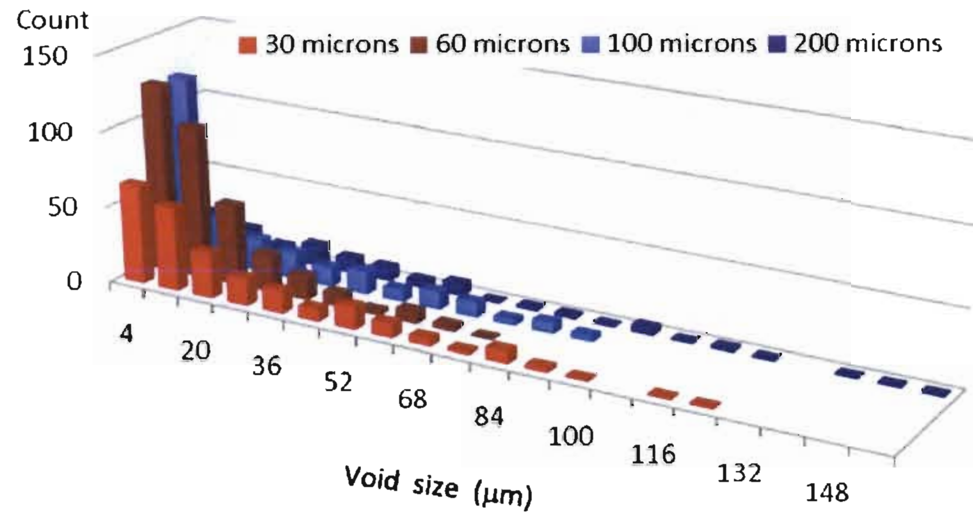


Damage Statistics from 2D optical analysis

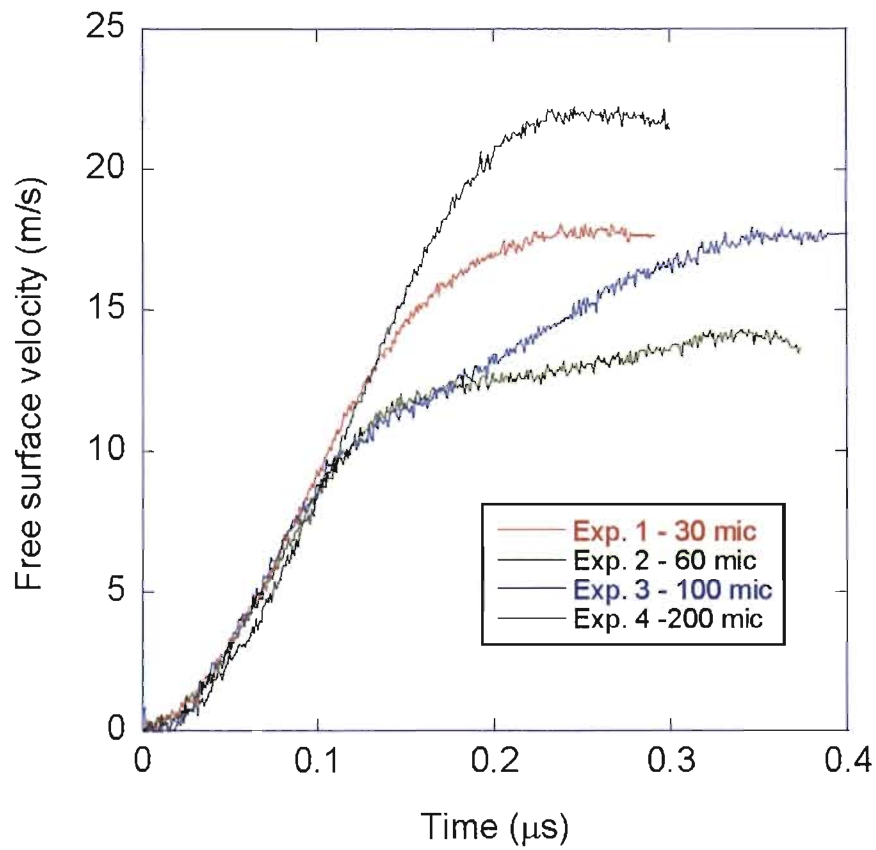
Experiment	Grain size	Number of voids	Void area fraction (%)	Avg Void diameter (um)
1s-1430	30 um	236	0.496	38.1
1s-1440	60 um	343	0.249	22.7
1s-1476	100 um	267	0.416	33.0
1s-1434	200 um	111	0.507	55.1

Void area fraction does not follow a linear trend.

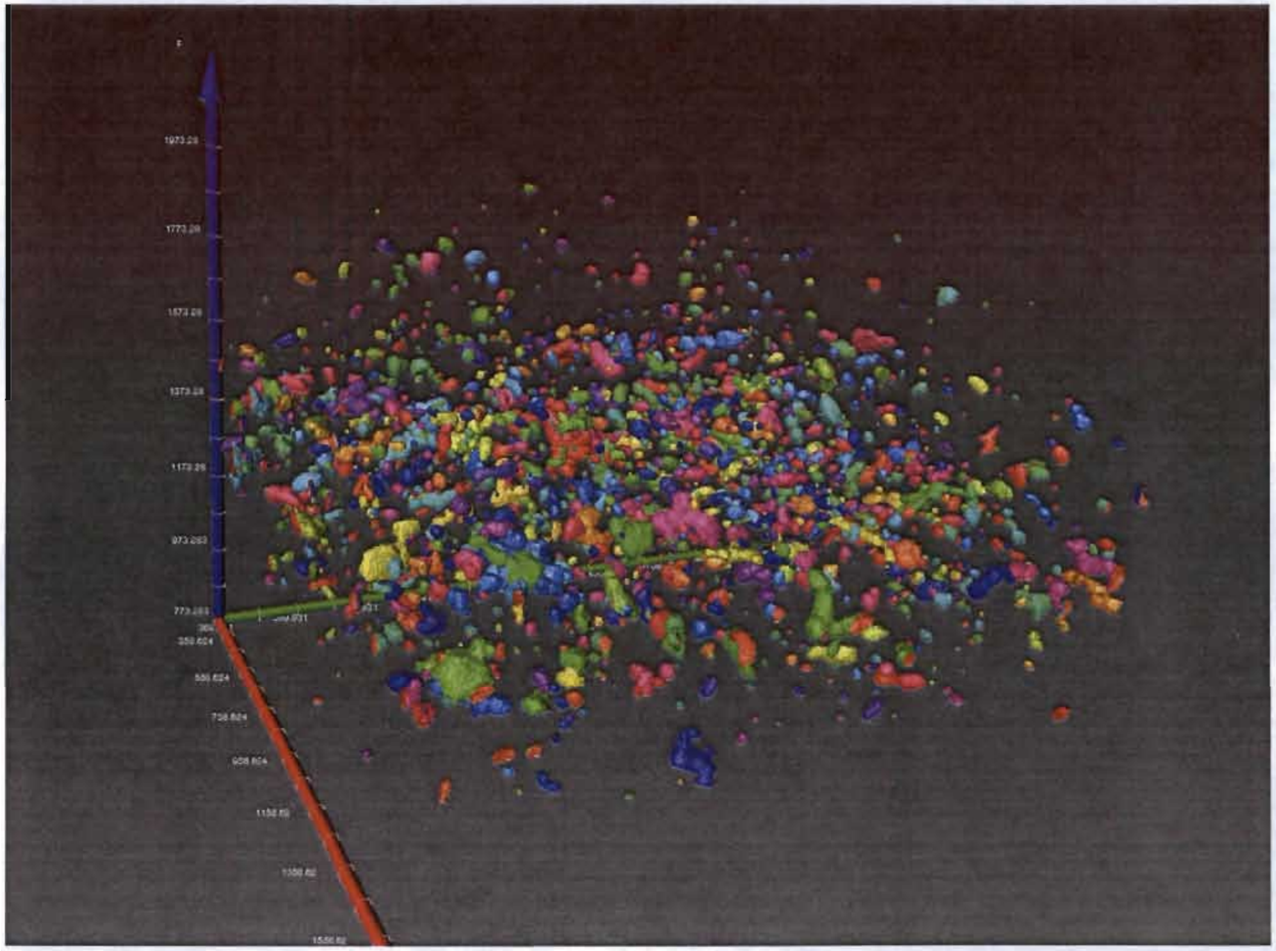




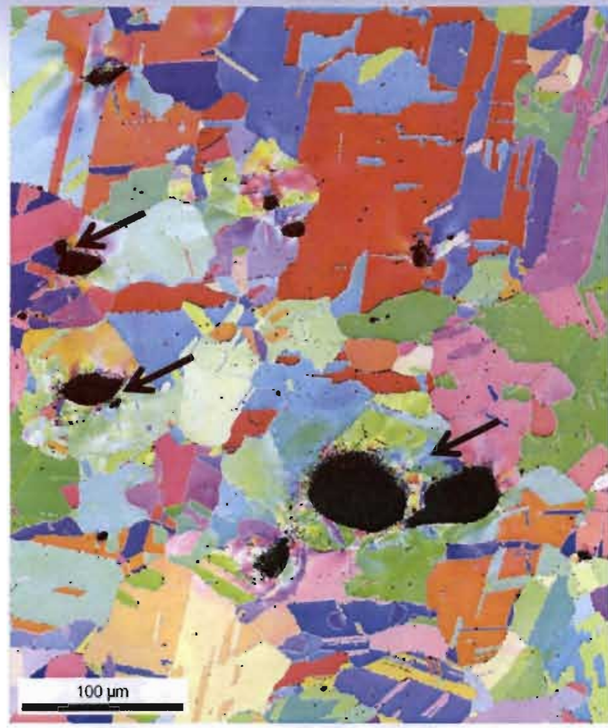
VISAR results show the difference between a slower rate growth process of individual voids and the faster process of coalescence.

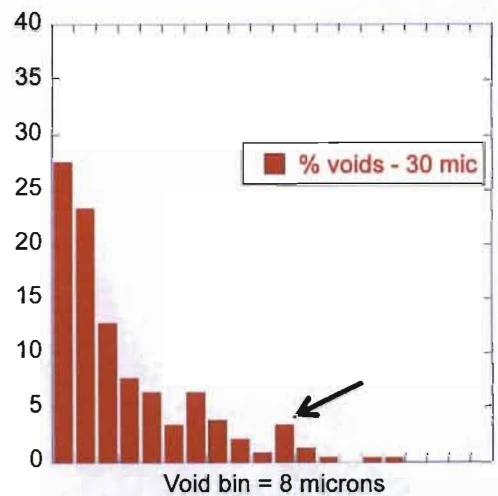


3D microtomography is providing new insight into dynamic material response.



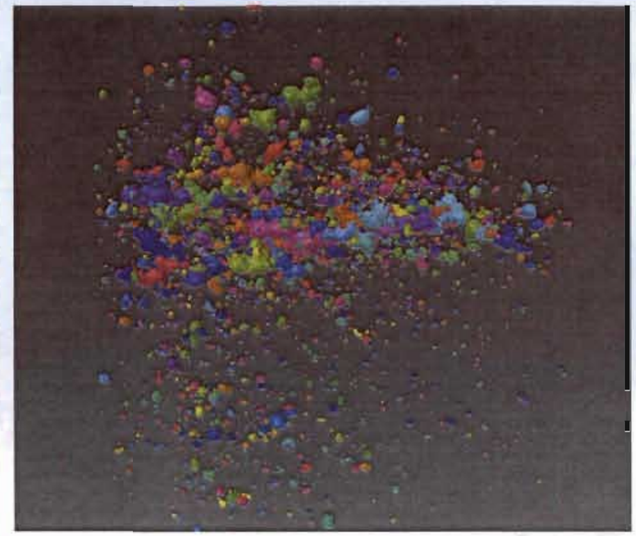
30 um samples show largely coalesced voids.

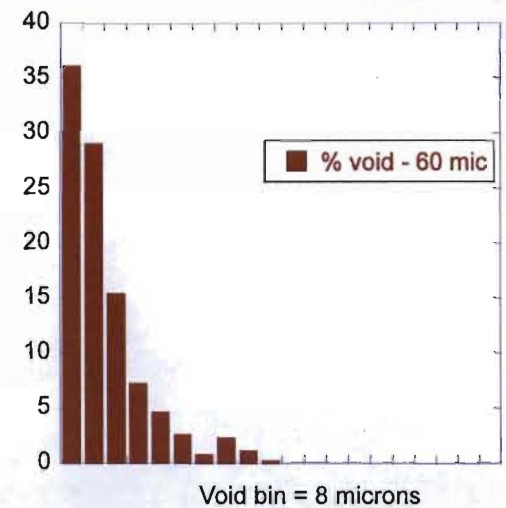




Both EBSD (2D) and tomography (3D) show larger voids. Arrows in OIM maps (and plot) show coalescence of small voids.

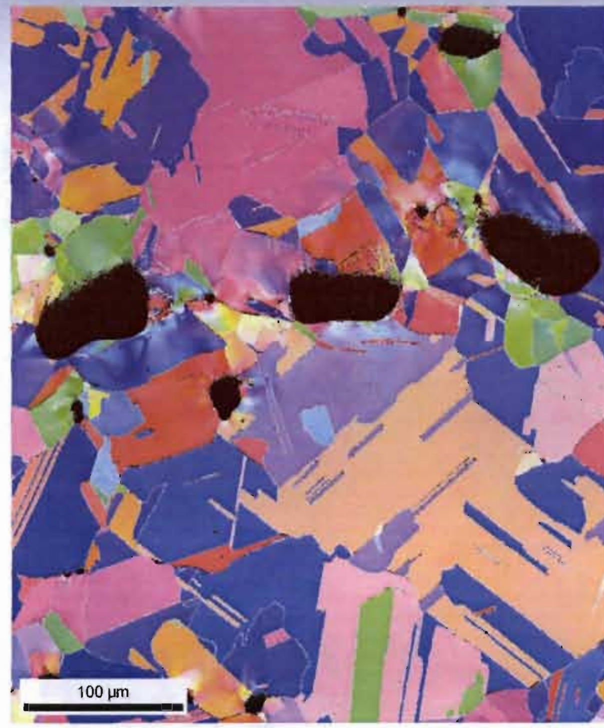
60 um samples show small isolated voids that do not indicate significant coalescence.

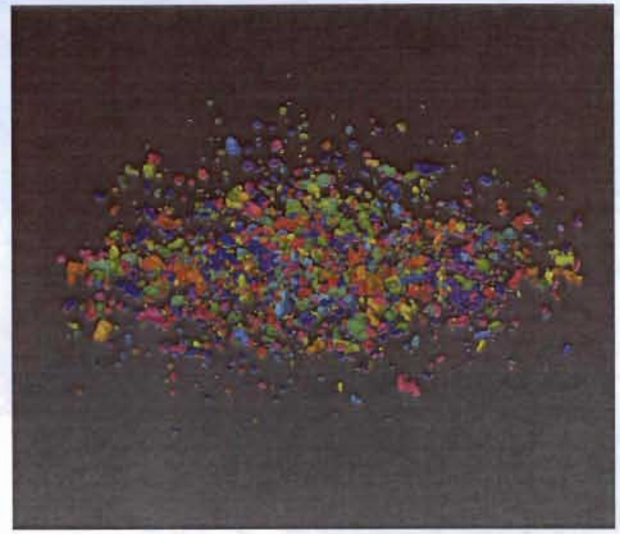


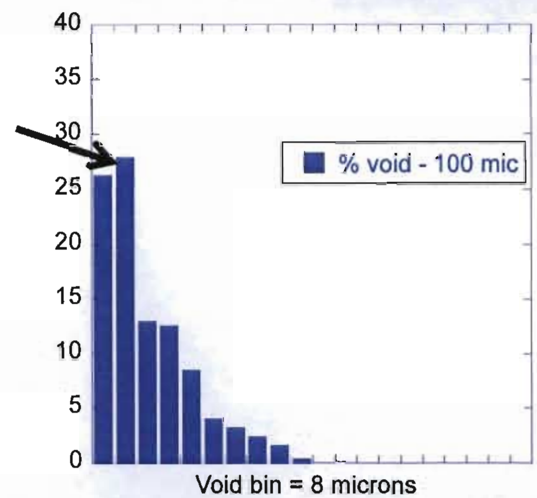


Both EBSD (2D) and tomography (3D) show smaller and isolated voids as compared with the 30 μm case.

100 um samples show some voids have begun to coalesce, but voids largely remain isolated.

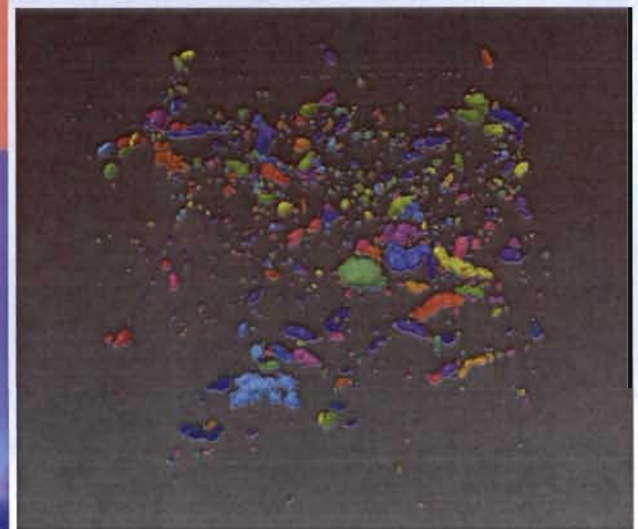


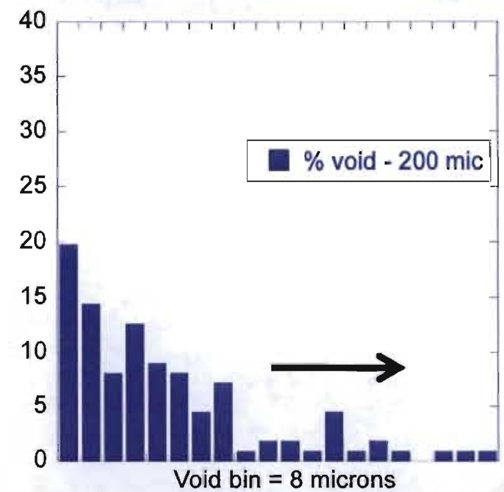




EBSD (2D) isolated voids (as 60 μm) but some started to grow. That is reflected on the plot showing the void distribution (arrow).

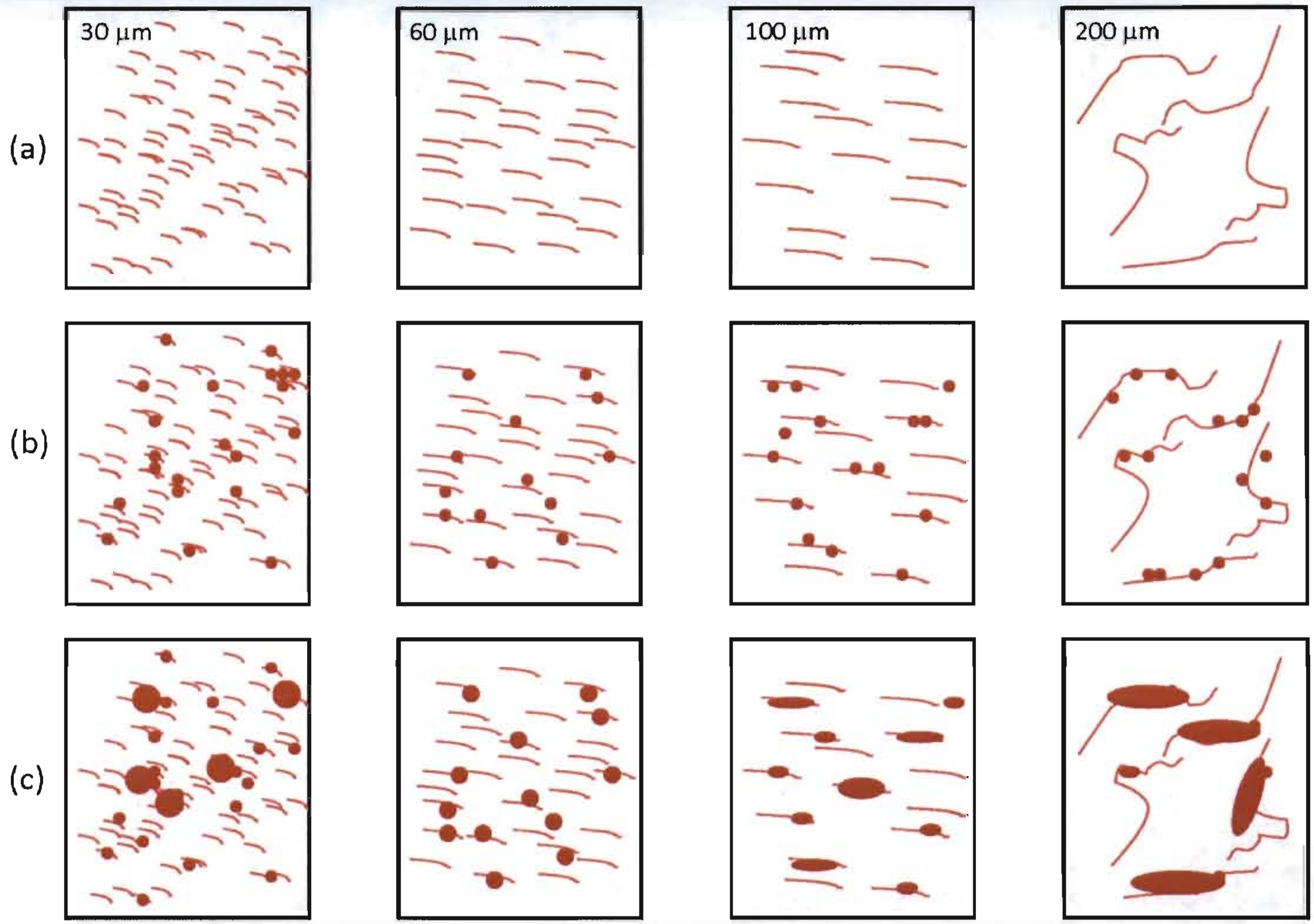
200 um samples show voids have grown and coalesced and damage is well developed.





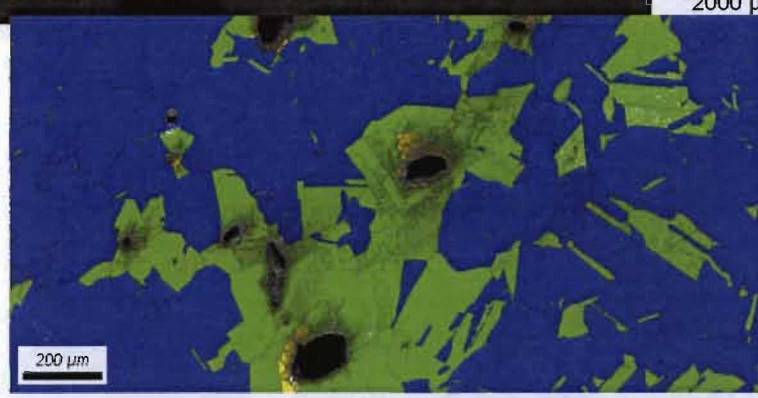
Both EBSD (2D) and tomography (3D) show the largest voids, also reflected on the distribution plot (arrow).

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



What are the mechanisms controlling coalescence of voids?

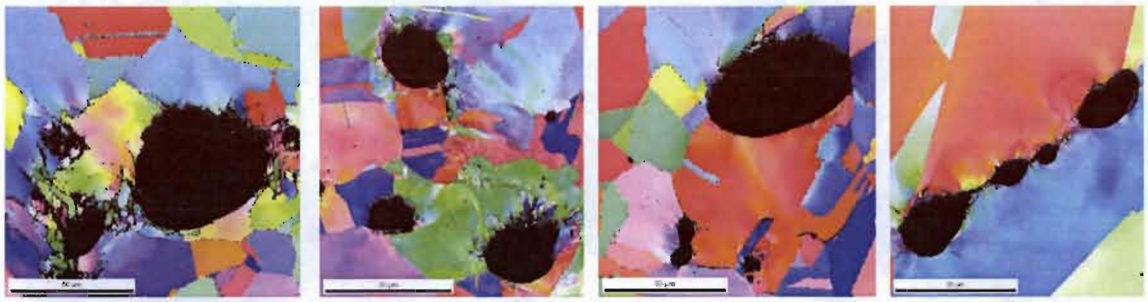
Regions of enhanced misorientation may lead to damage coalescence



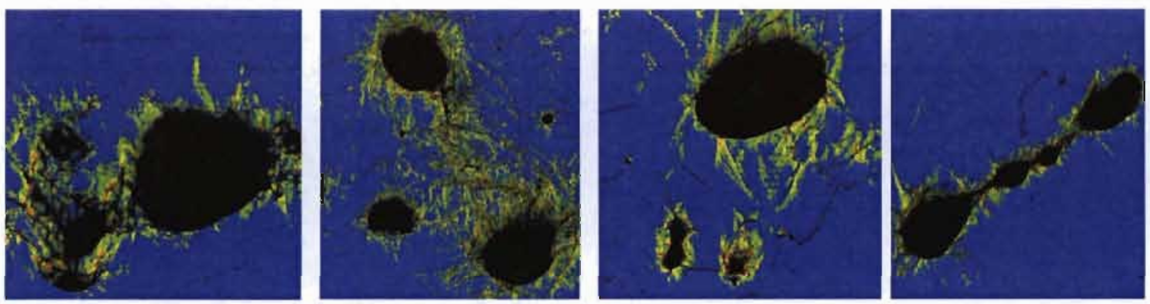
	Min	Max	Total Fraction	Partition Fraction
(blue)	0	0.6	0.971	0.971
(green)	0.6	1.7	0.026	0.026
(yellow)	1.7	4	0.000	0.000
(orange)	4	8	0.000	0.000
(red)	8	16	0.000	0.000

Boundaries: <none>

Average kernel misorientation relates plastic deformation to microstructural misorientation



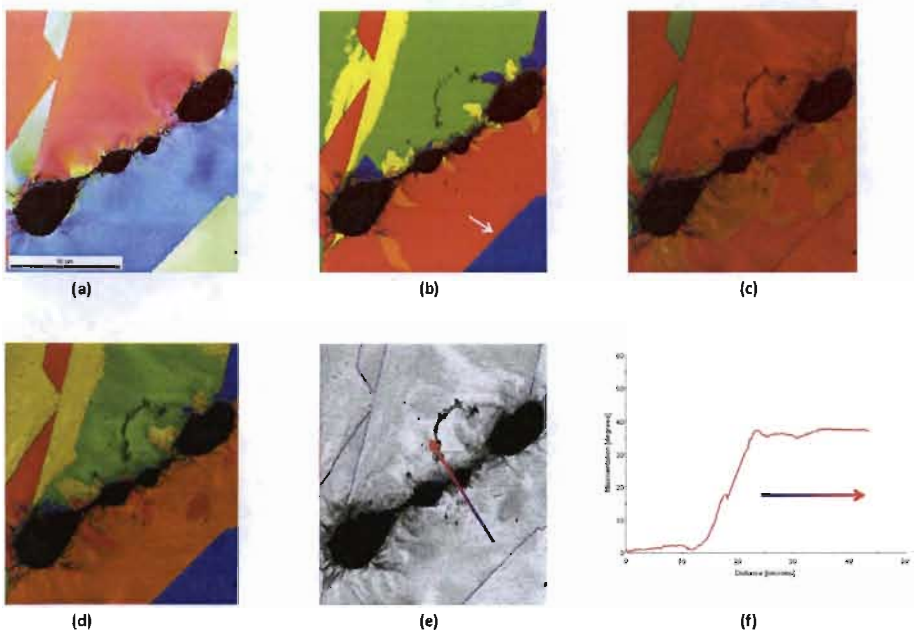
(a) (b) (c) (d)

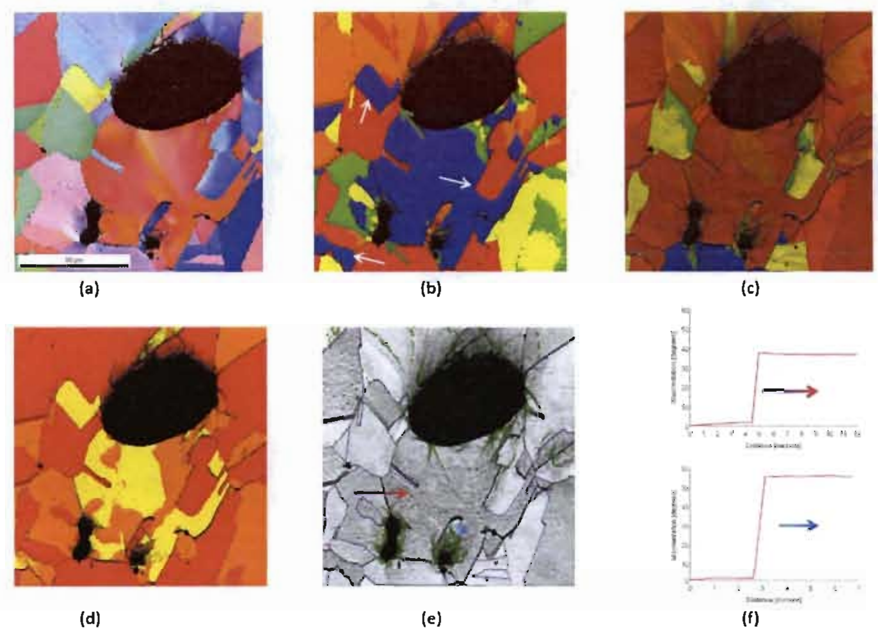


(e) (f) (g) (h)

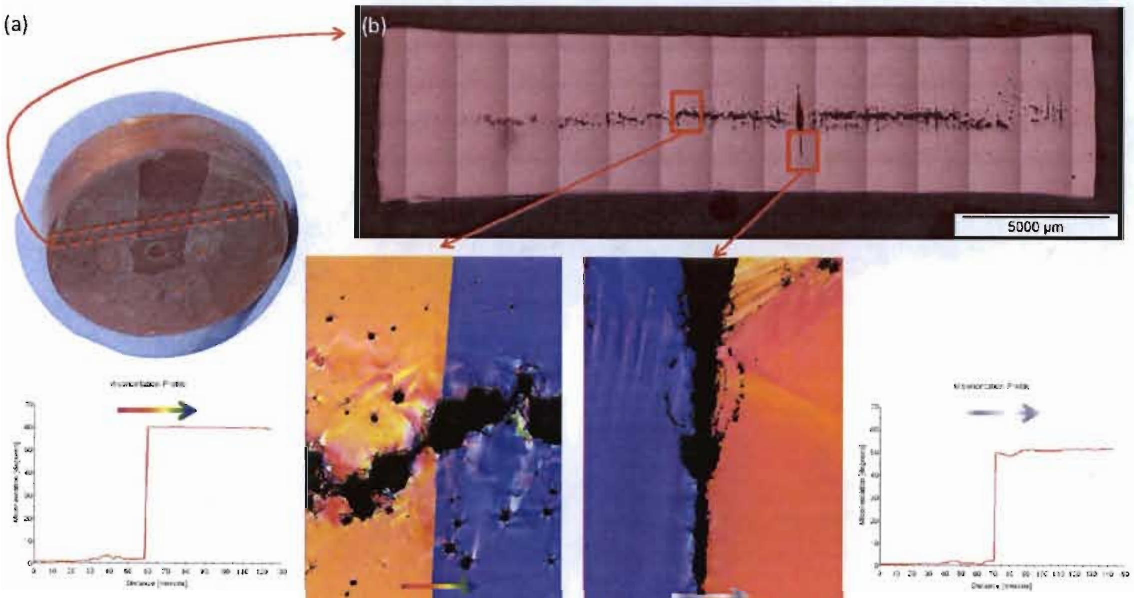
- Coalescing voids show highly localized regions of misorientation
- Individually growing voids show overlapping regions of misorientation which may indicate the pathway for coalescence to begin.

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





Grain boundary type does seem to have an influence.



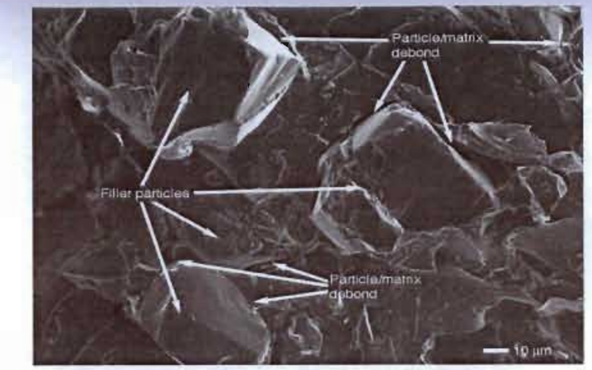
Σ3 boundary (60°)

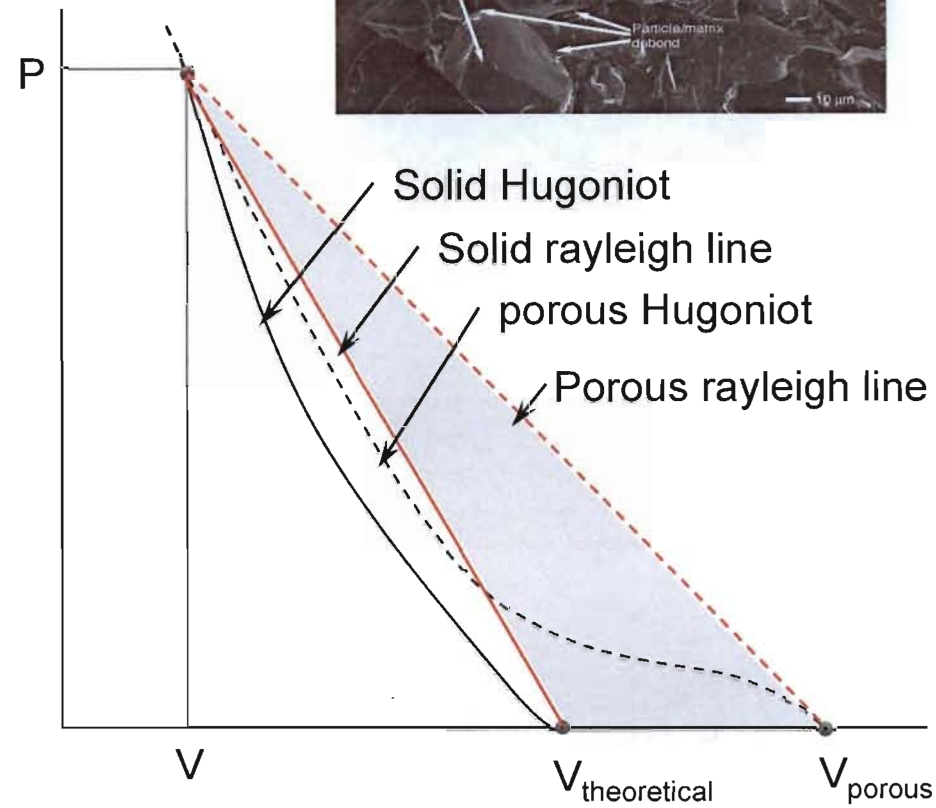
High angle boundary (~50°)

- 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°

Shock response of Uranium oxide powders began as a method for the study of extreme high temperatures of nuclear reactor temperature excursion.

- **The energy required to collapse the porous structure dynamically is translated into kinetic energy of the individual molecules.**
- **Shock compression of solid metals does not reach high enough temperatures.**
- **Shock compression of porous materials (density below theoretical) results in much higher temperatures.**





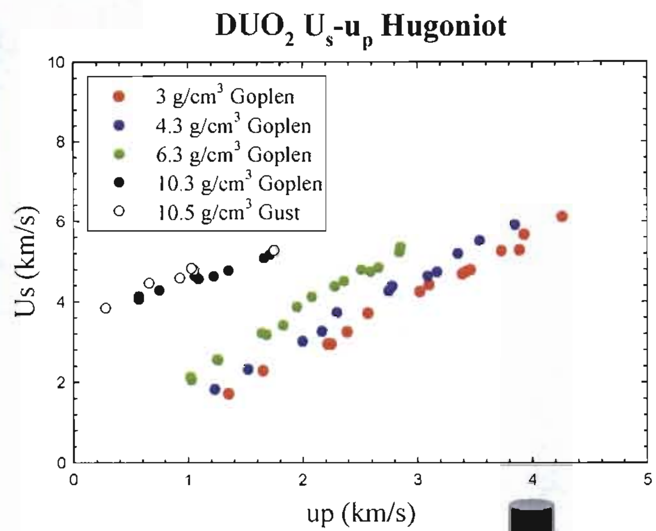
Measurement of the shock Hugoniot is used to develop an EOS.

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

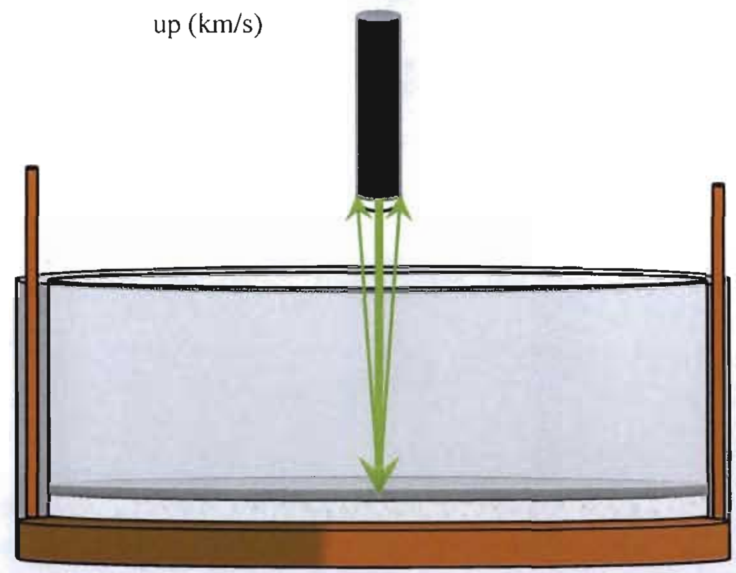
$$\rho_0 U_S = \rho(U_S u_p) \qquad \textit{conservation of mass}$$

$$P - P_0 = \rho_0 U_S u_p \qquad \textit{conservation of momentum}$$

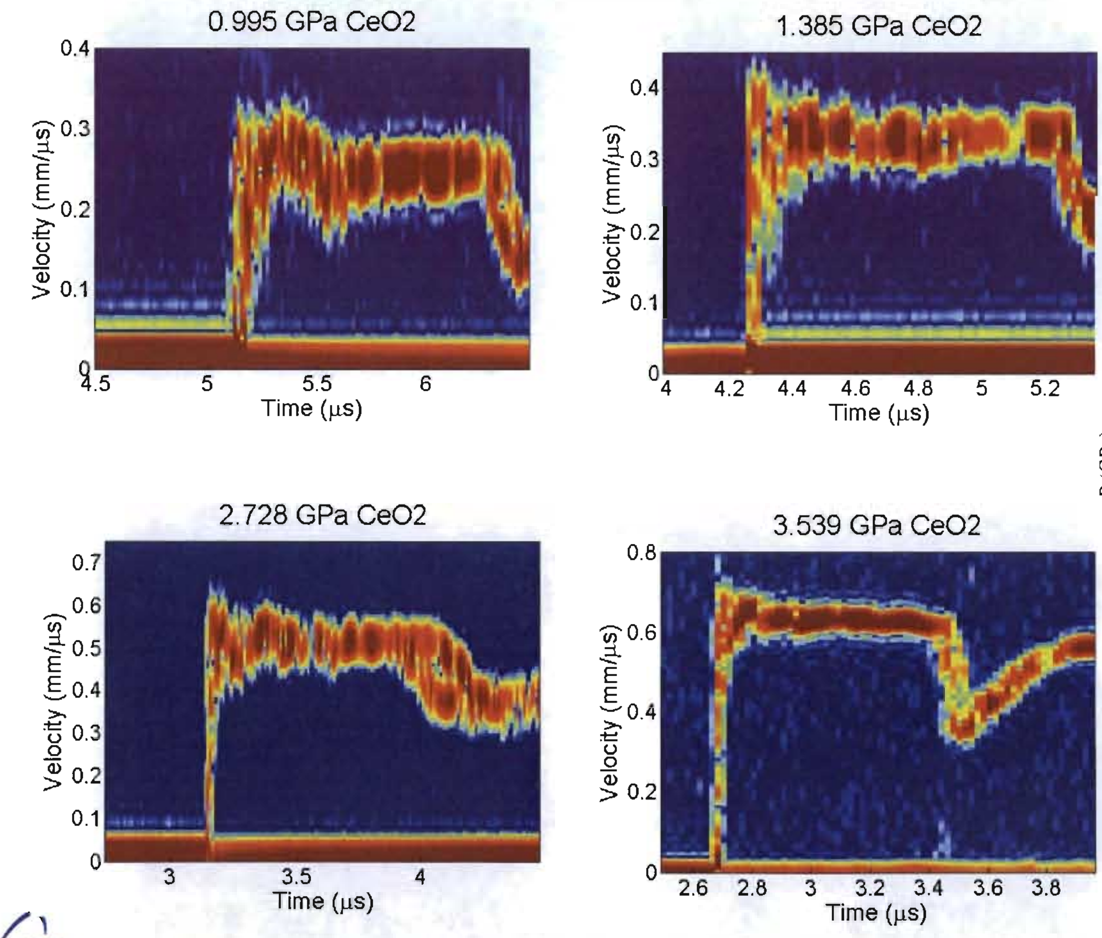
$$P_0 u_p = \left[(E - E_0) - \frac{u_p^2}{2}\right]\rho_0 U_S \qquad \textit{conservation of energy}$$

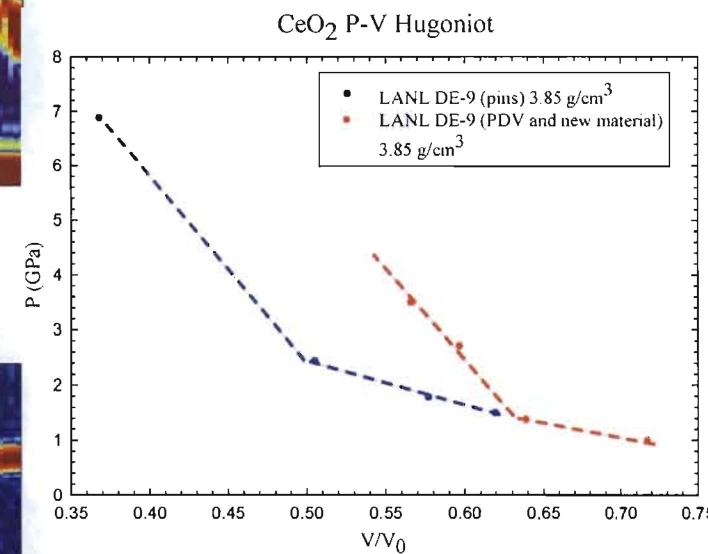


Time of arrival diagnostics are used to measure transit times for a direct observation of U_s.

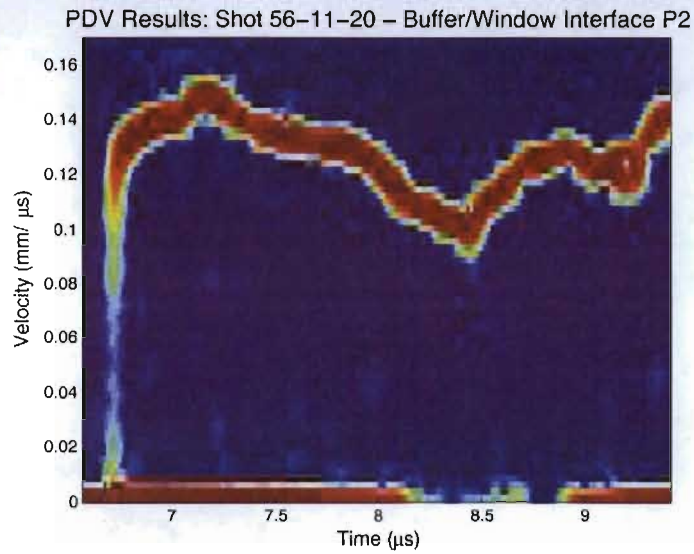


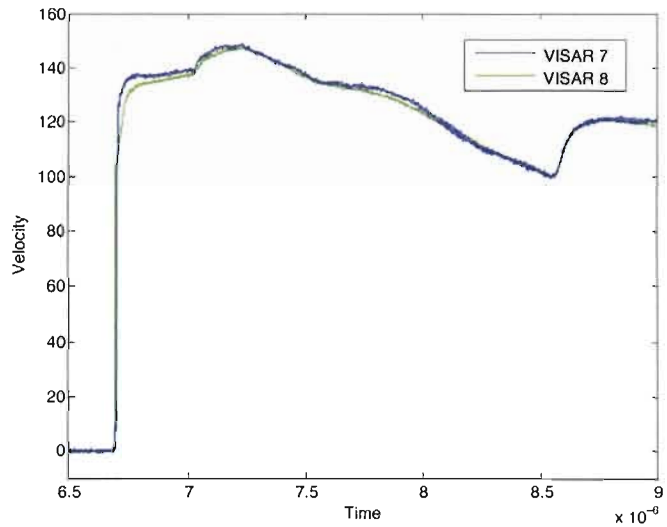
CeO_2 velocimetry results highlight the nature of the compaction process.



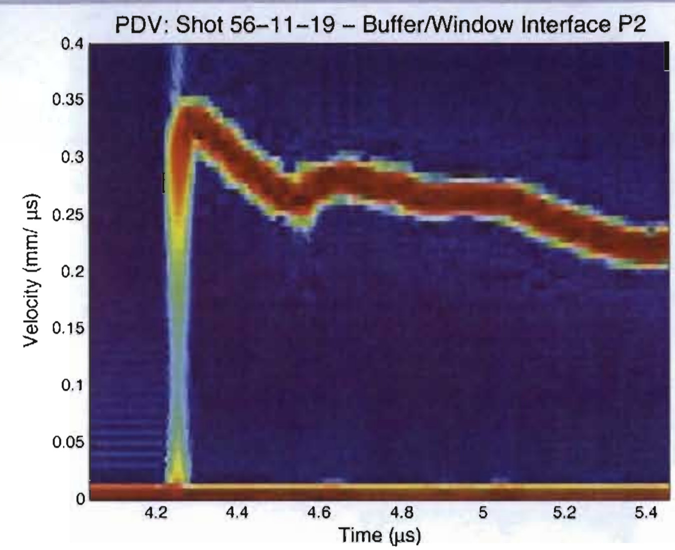


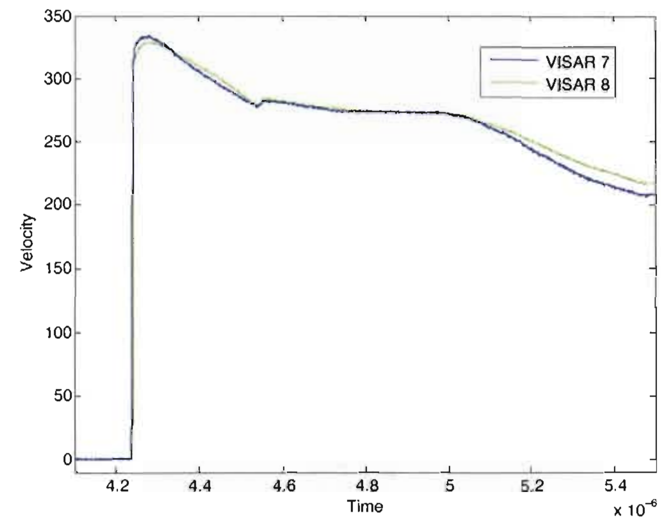
Improved diagnostic techniques are used to probe compaction behavior





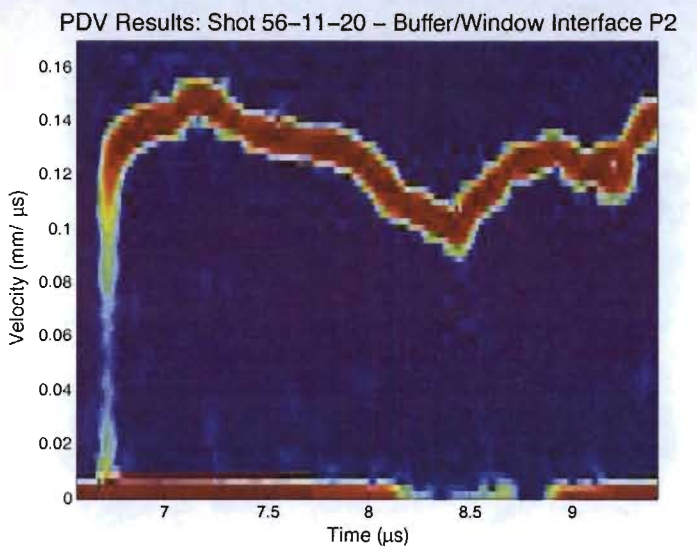
Impact Velocity - 219 m/s

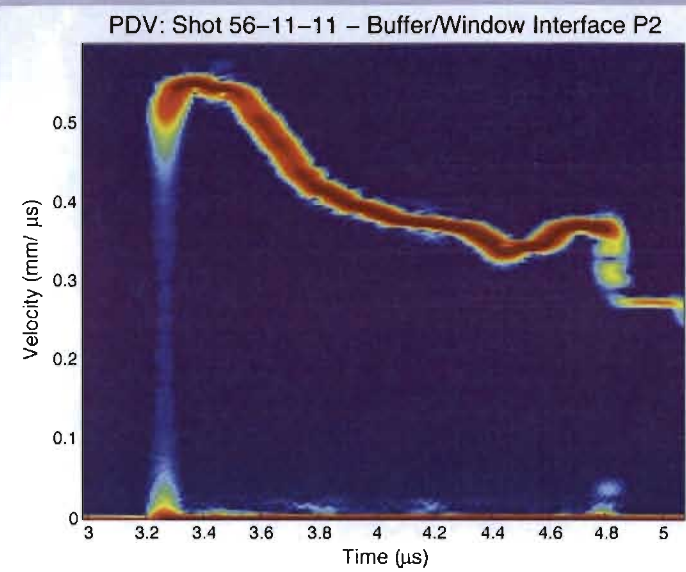


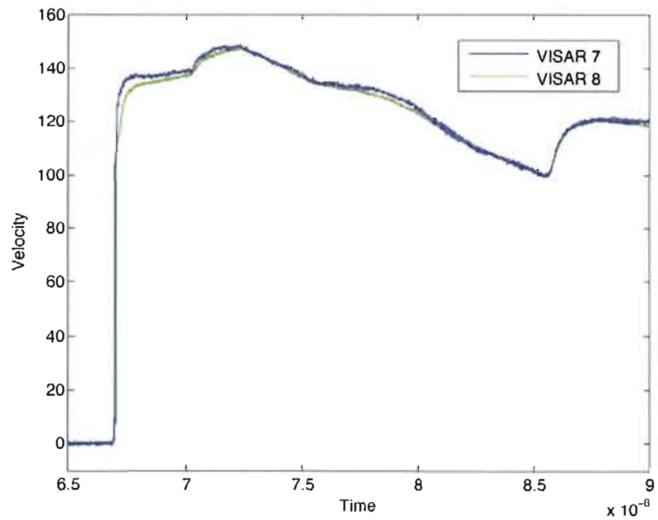


Impact Velocity = 407 m/s

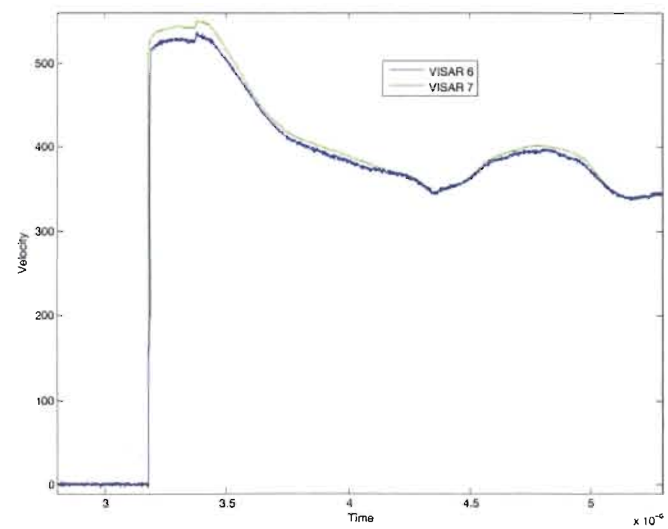
Initial relaxation may be displaying a pressure dependence.





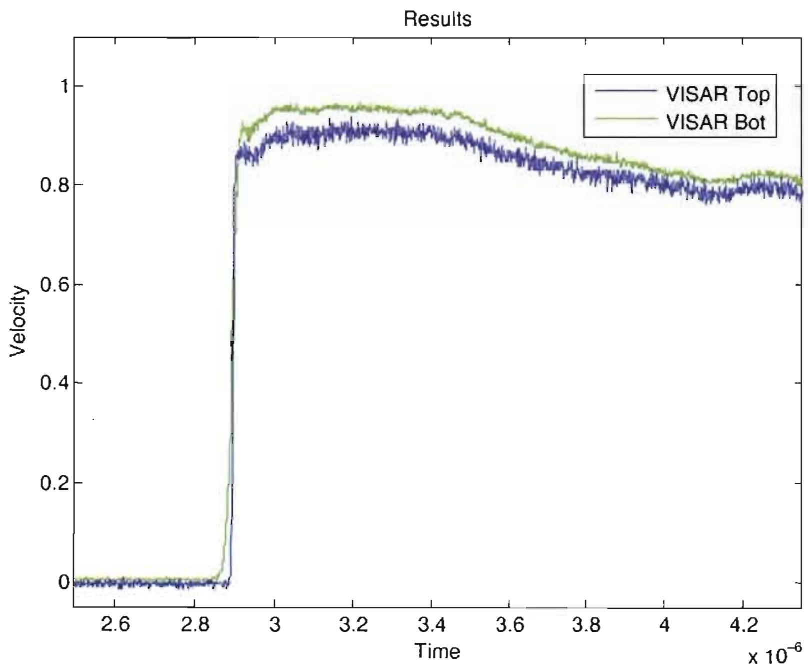


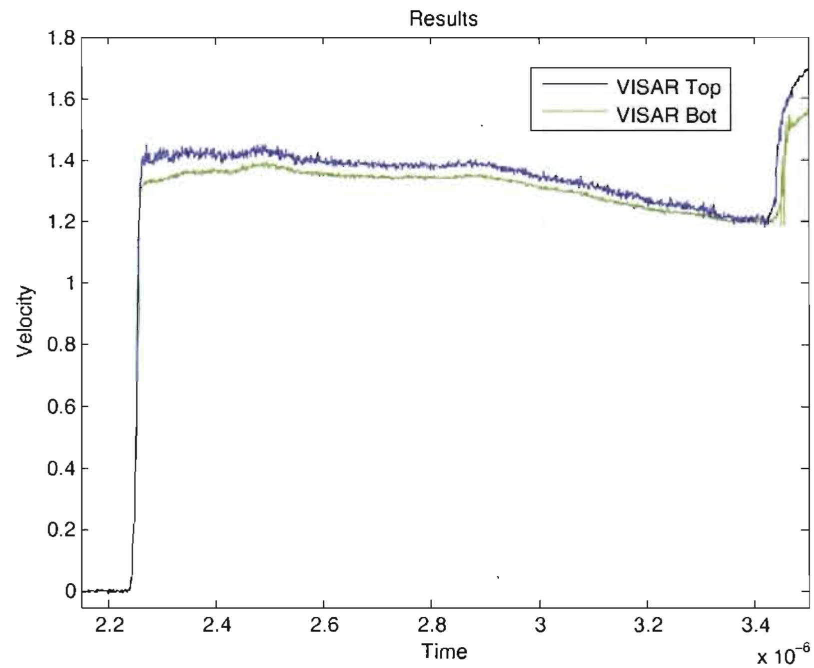
Impact Velocity - 219 m/s



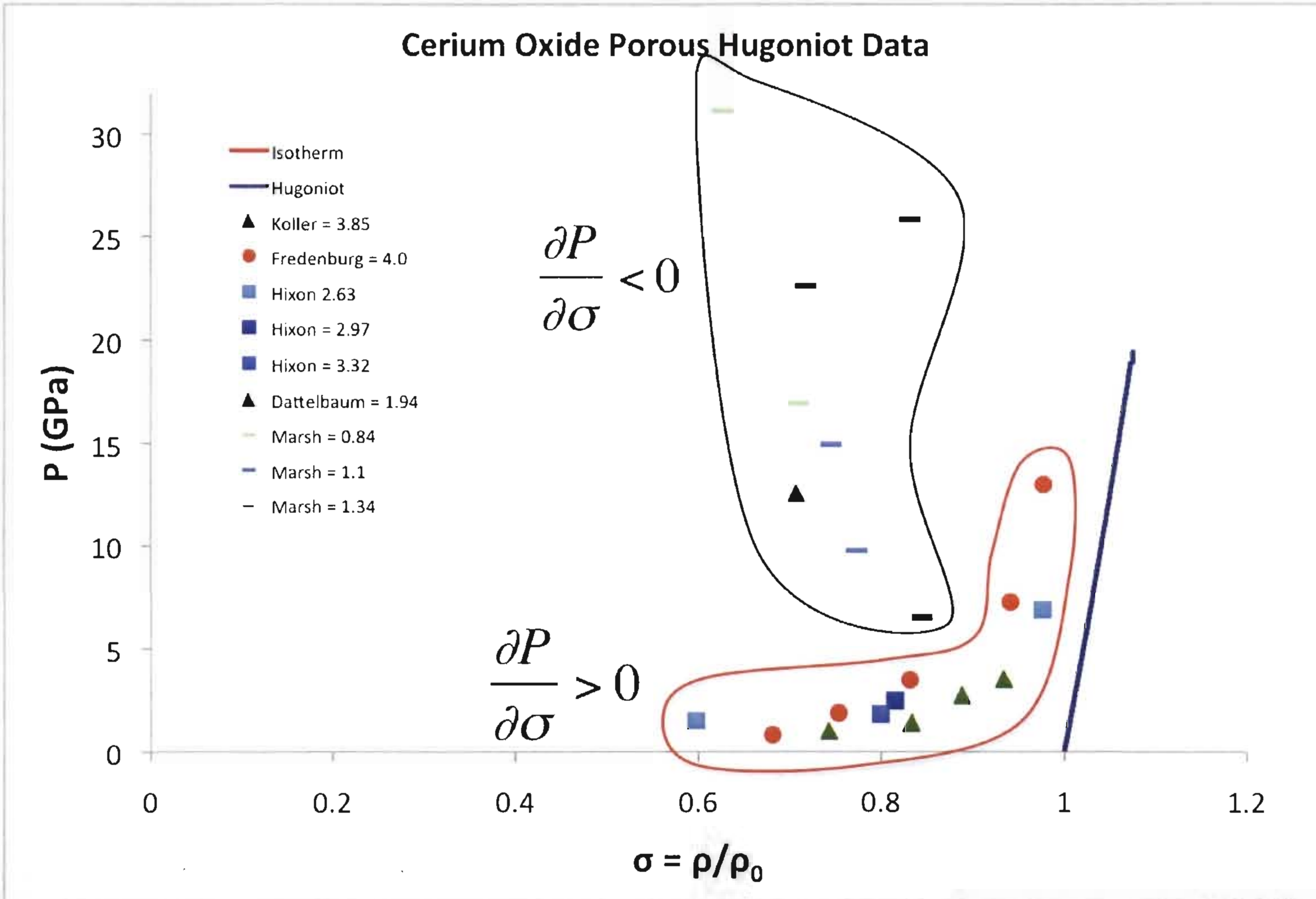
Impact Velocity = 626 m/s

Can we overdrive compaction?

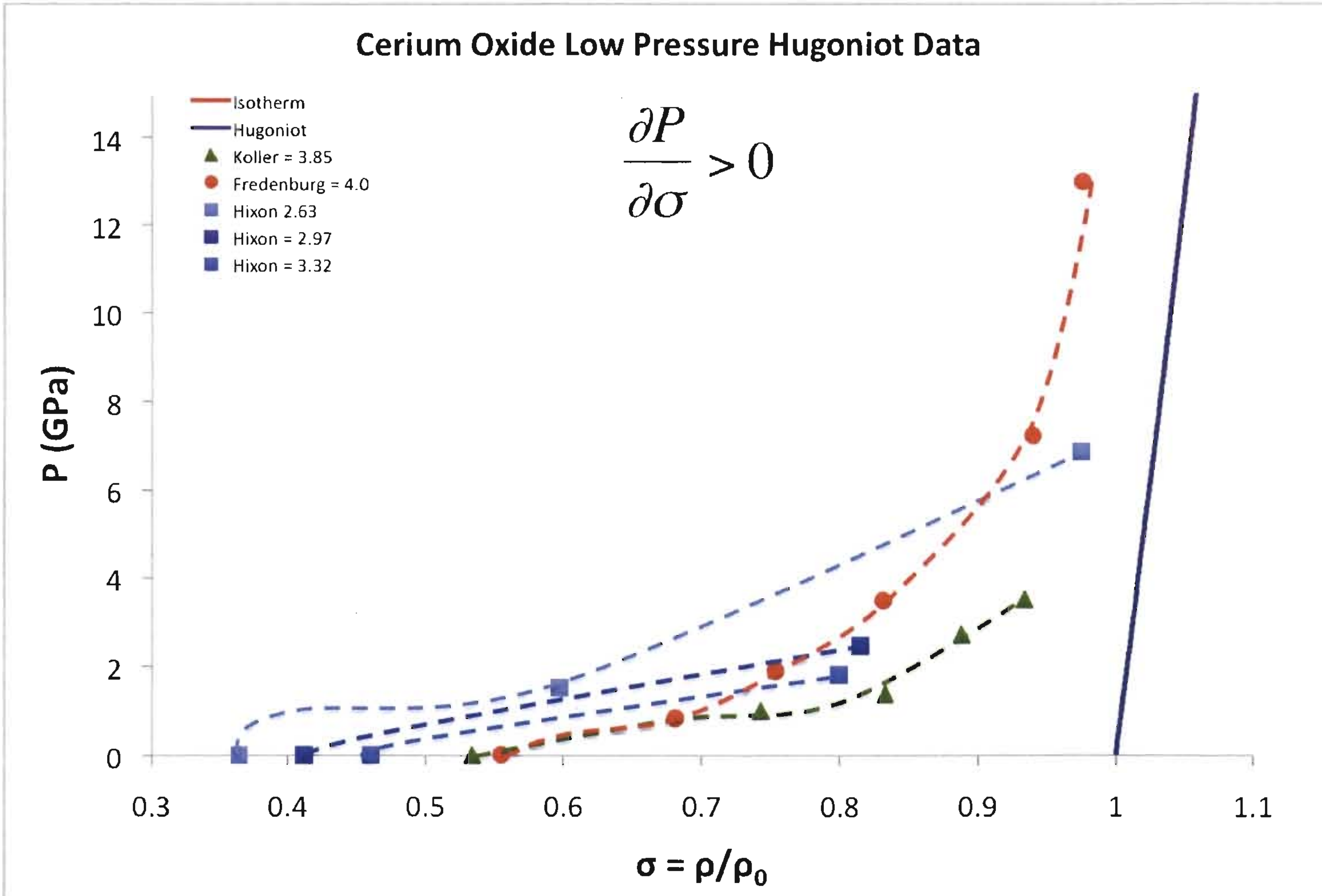




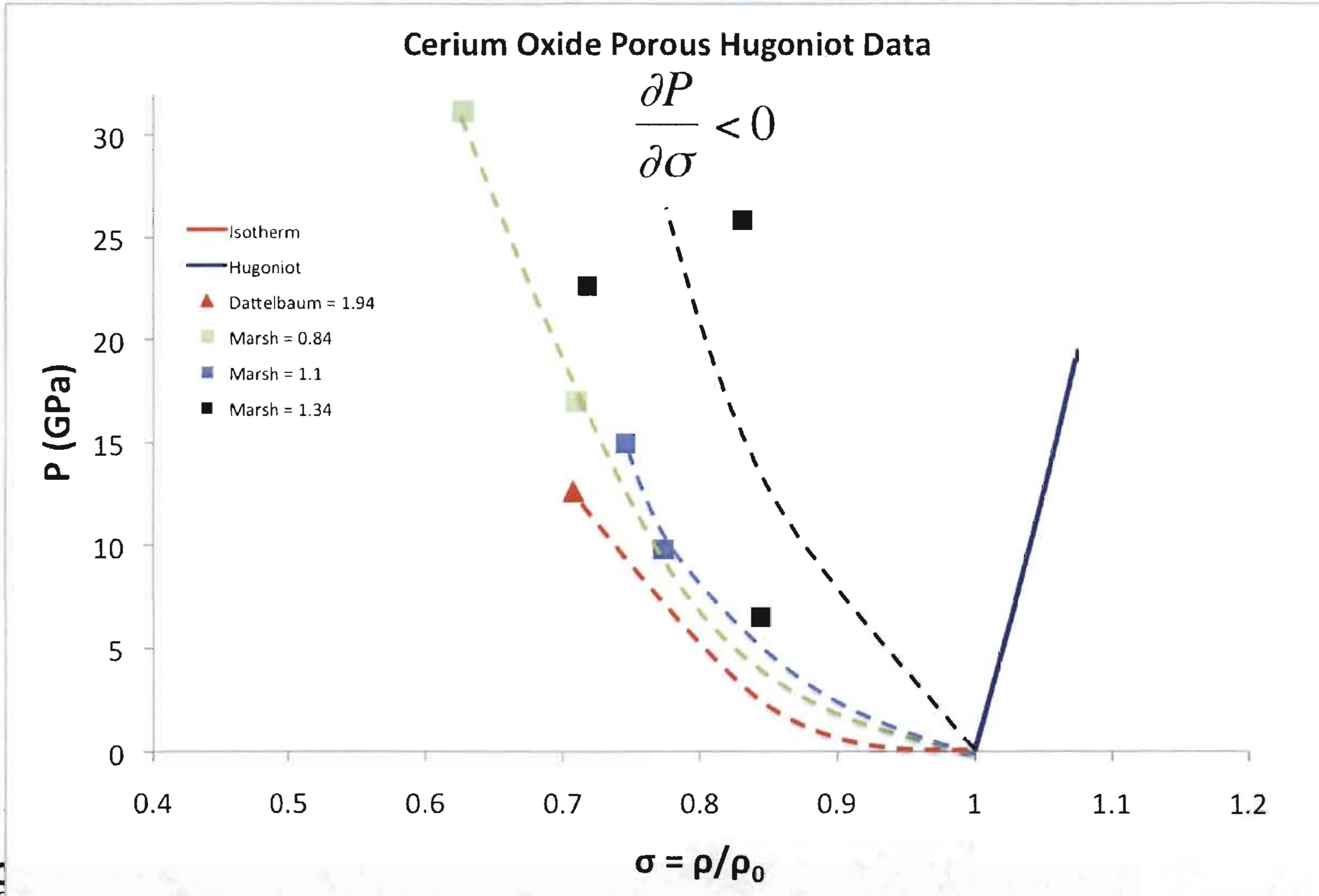
Strength and compaction of porous media is another area of interest.



Normal compaction regime indicates a dependence on morphology.



Anomalous compaction regime indicates a dependence on morphology.



Summary

- 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 individual void growth to coalescence dominated.
- An understanding of mechanisms dominating damage regimes is necessary to 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.
- New morphology studies on CeO_2 powder are showing significant influence on compaction.
- Compaction processes do not appear to be overdriven at high pressures.

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