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

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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

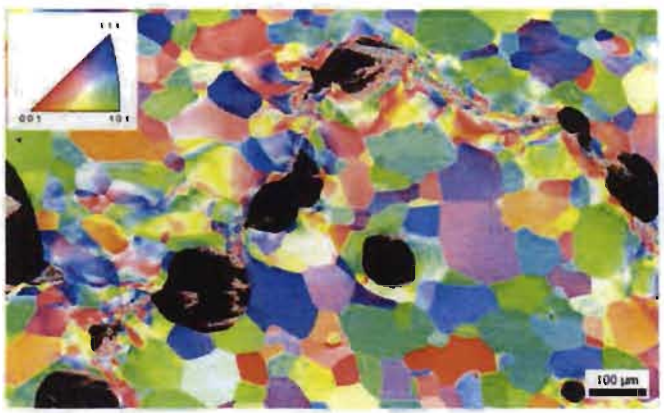
APS SCCM

June 30, 2011

LDRD: Isolating Kinetic and Spatial Effects in Dynamic Damage Evolution

A collaborative experimental and theoretical center of expertise focused on the study of the meso to macro-scale dynamic ductile damage and failure of metallic materials .

Goal: Explain and predict the ductile damage process in polycrystalline metallic materials from the nucleation of pores through ultimate failure for any dynamic loading profile applied to materials of national strategic and economic importance for application specific design of new materials.

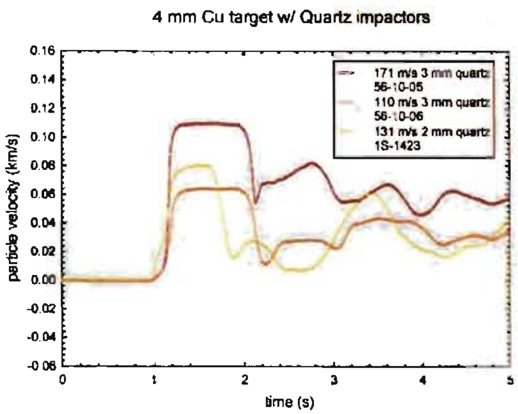


High Resolution Orientation Image Mapping

Polycrystal Plasticity Theory

LDRD: Isolating Kinetic and Spatial Effects

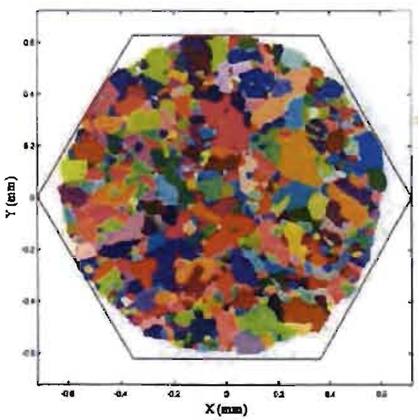
Shock Loading



Sample Recovery

High Resolution OIM

World – Class Experiments and Metallography

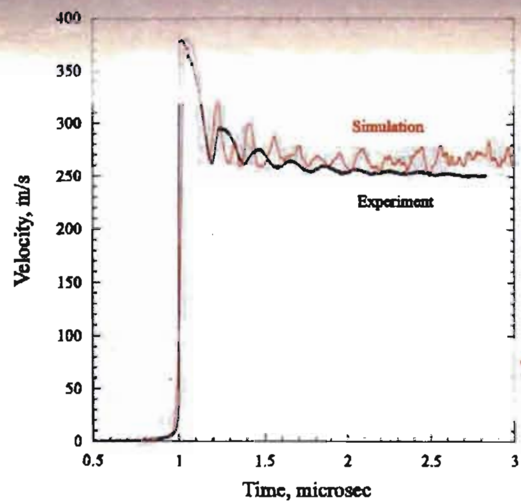


3D OIM Tomography (CMU)

3D Serial Section OIM

3D Microtomography

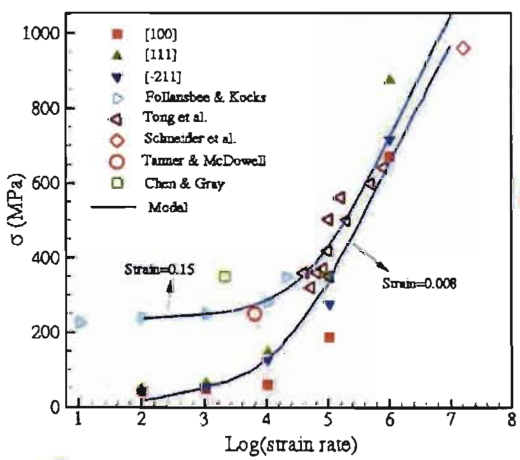
LDRD: Isolating Kinetic and Spatial Effects

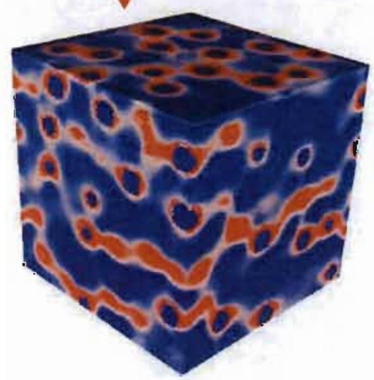


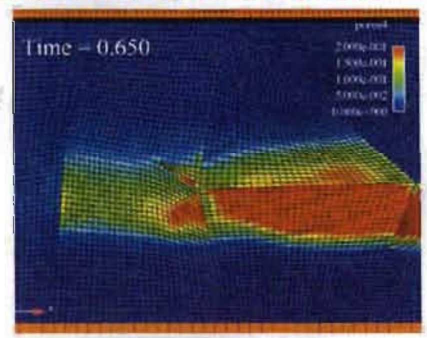
Macro-scale Continuum Theory

World – Class Large Deformation Theory and Simulation

Crystal Plasticity Finite Element Method







Single Crystal Continuum Theory

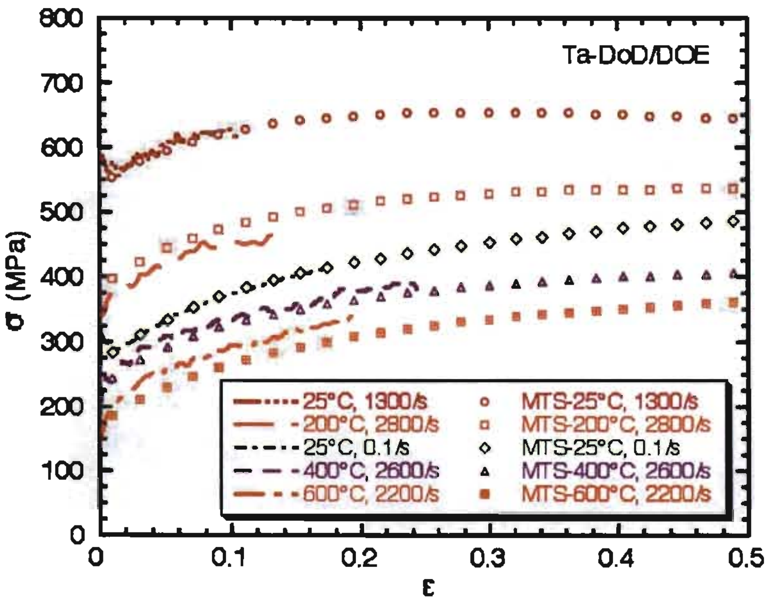
FFT Polycrystal Plasticity

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

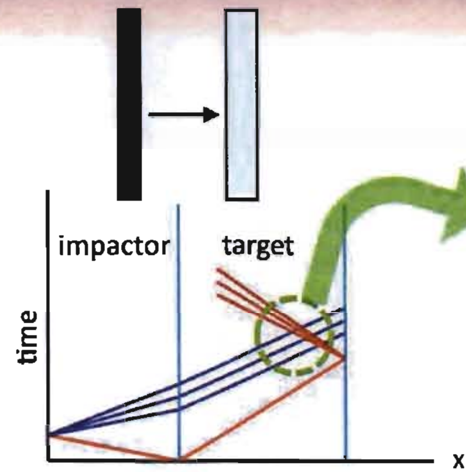
Typical Materials Characterization is at Low or Moderate Strain Rates



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"

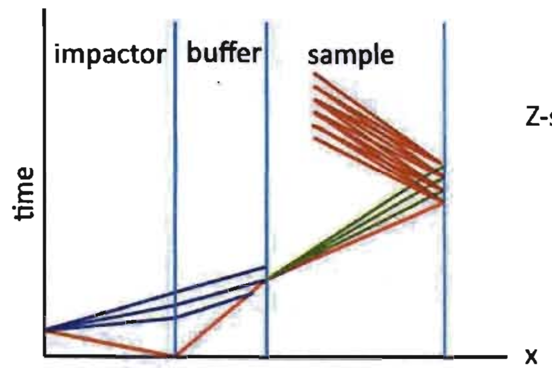
- These data frequently show that material response in dependent on strain rate
- Good understanding up to 10^3/s
- Would like to extend that understanding to 10^5-10^7/s
- These data are extrapolated to high strain rates to predict dynamic failures

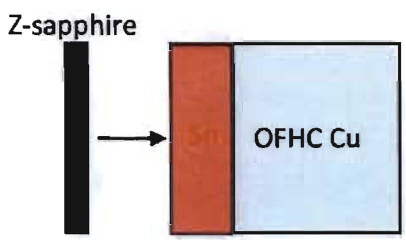
Experiments are designed to produce a dynamic state of tension damaging the material.



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.

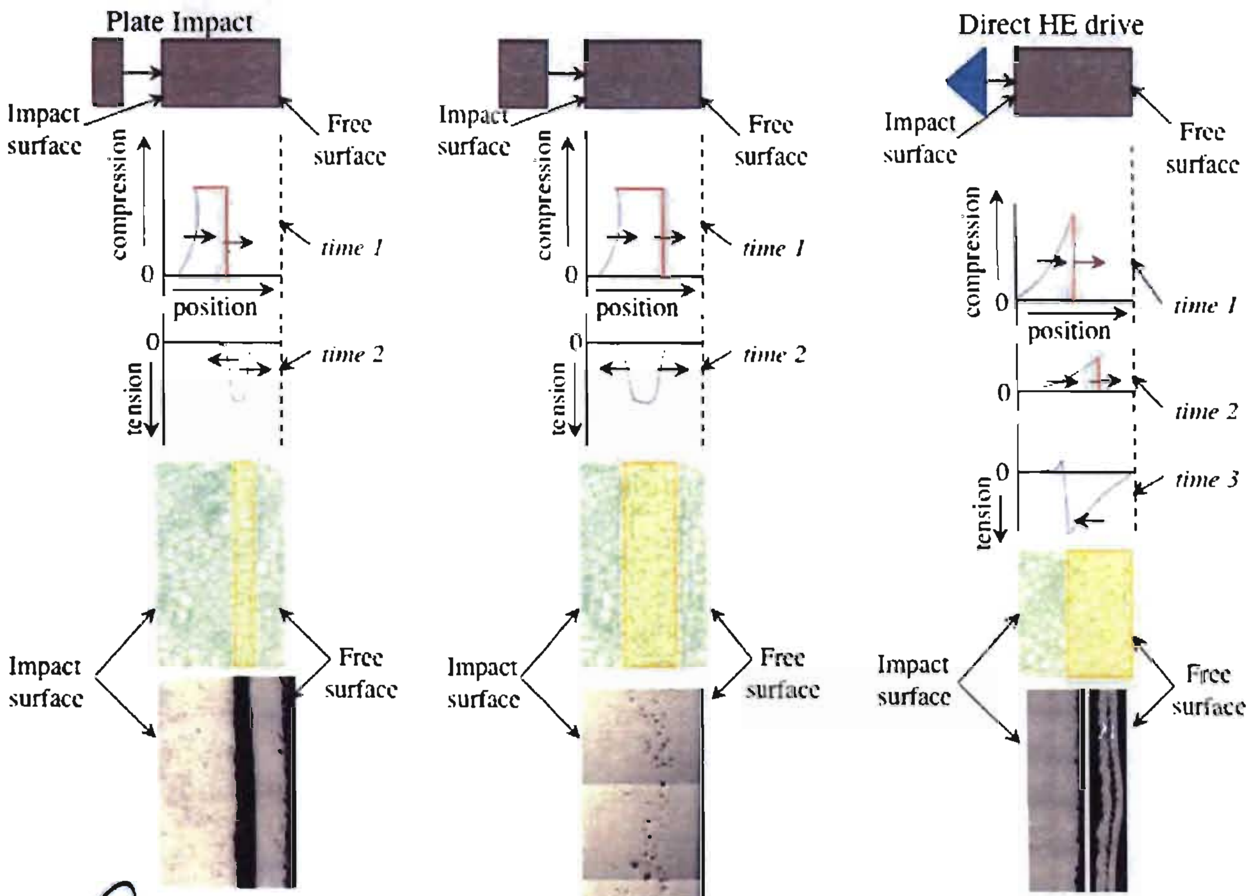


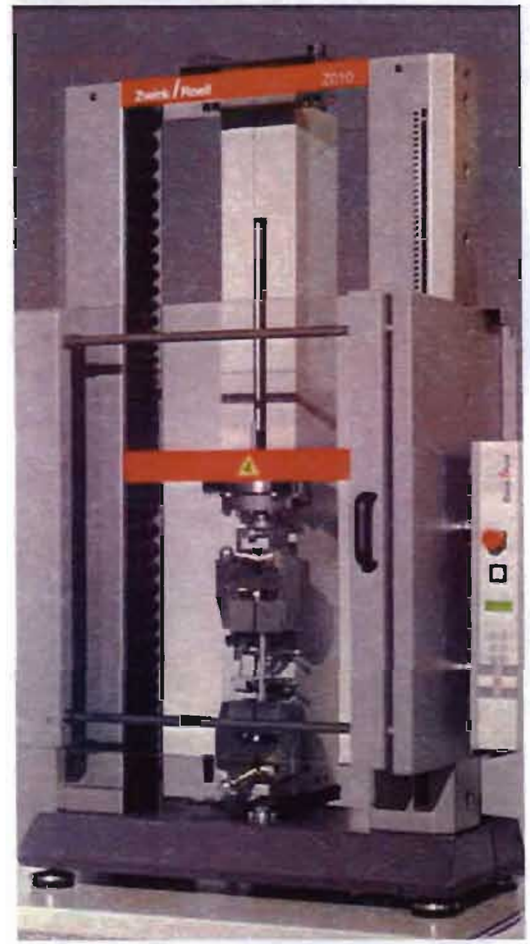


Triangle wave spall experiment

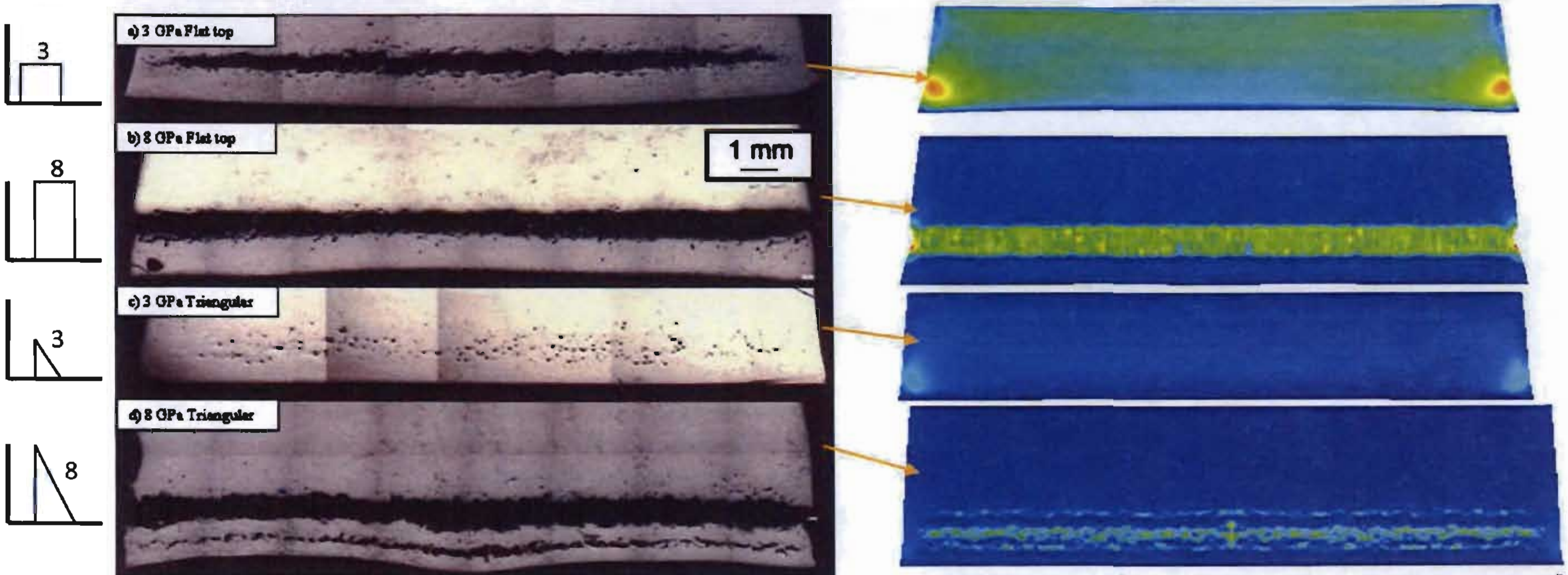
HE loading has triangular wave shape (Taylor wave)
Duration of release in plate impact experiment differs from that of a real Taylor wave; much shorter in the gun
Accomplished through an overtake experiment using a Tin buffer

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

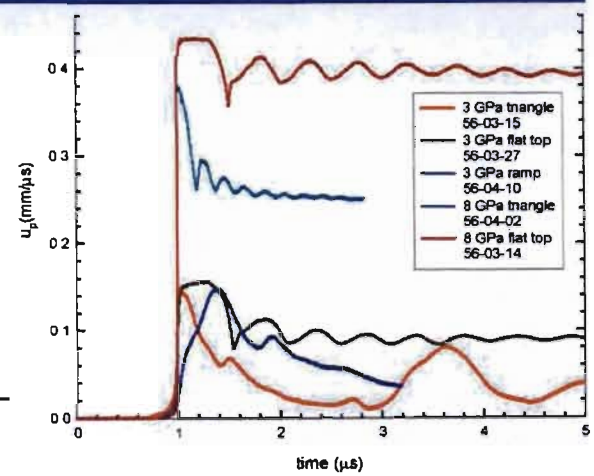




Shockwave Shape Significantly Influences Damage Evolution in a Metal



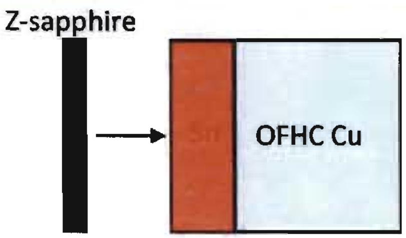
These simulations illustrate current damage model capabilities

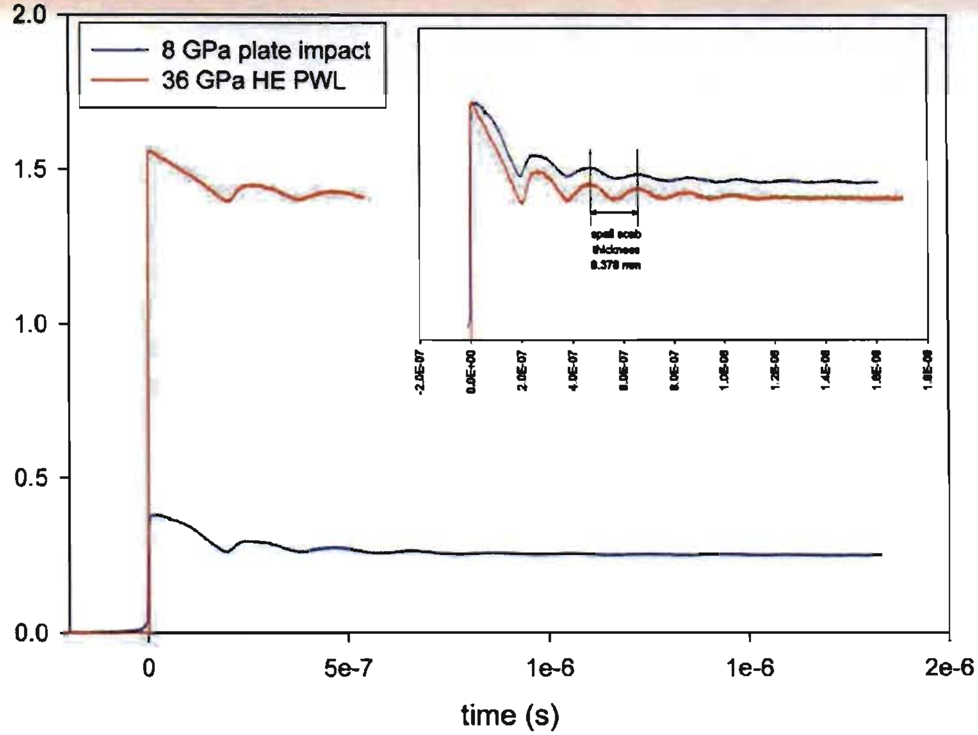


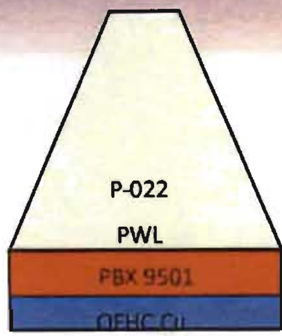
Koller and Cerreta, *J. Appl. Phys*, Nov. 2003

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

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

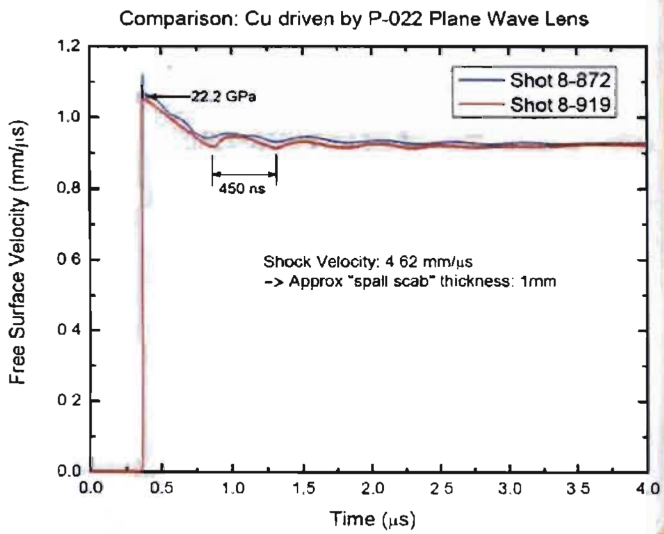






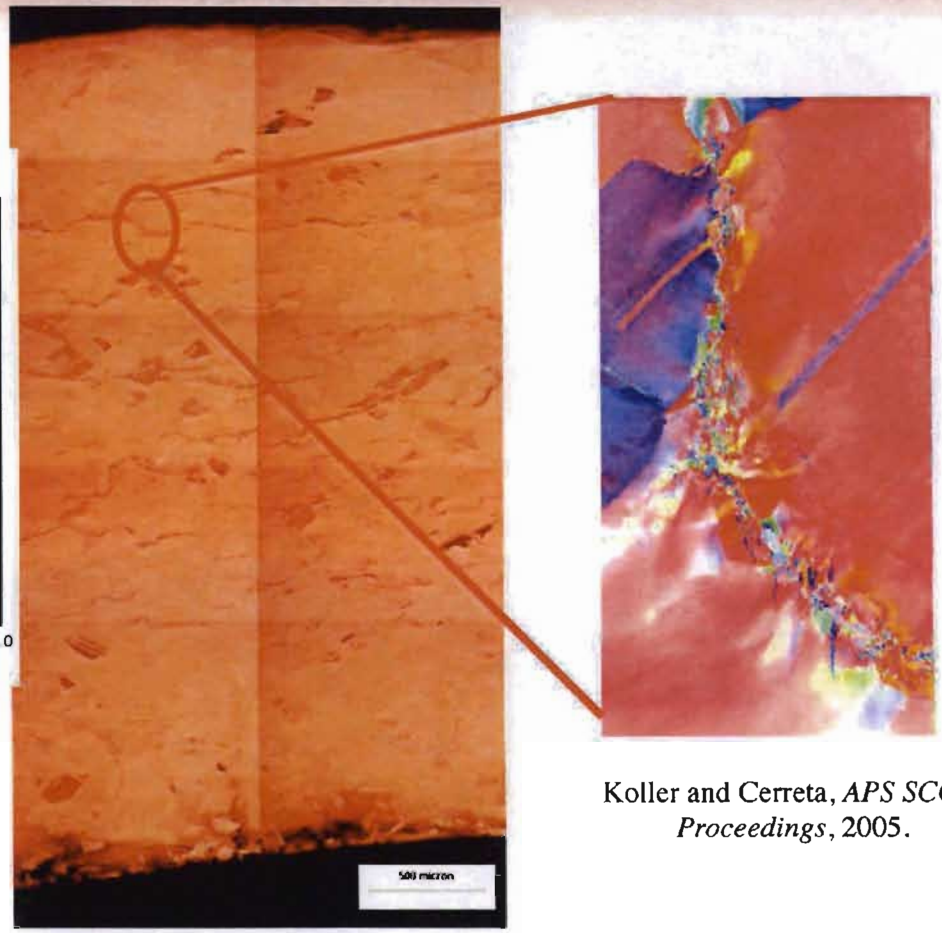
- Experiment shows that plate impact experiments can be used to explore a range of peak pressure states while maintaining the same strain rate on the release.
- When the 9501 booster was added the duration of the tensile pulse was shortened and the material spalled just as was seen in the plate impact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

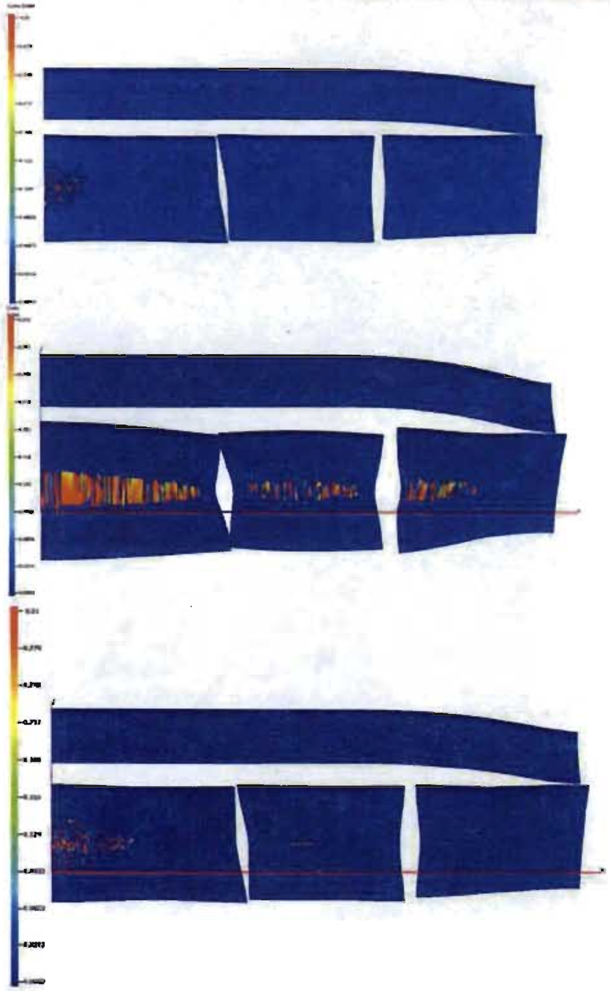
Direct HE

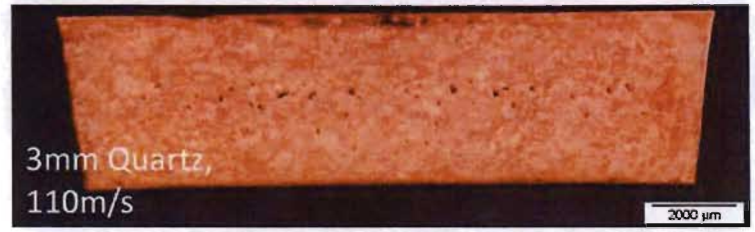


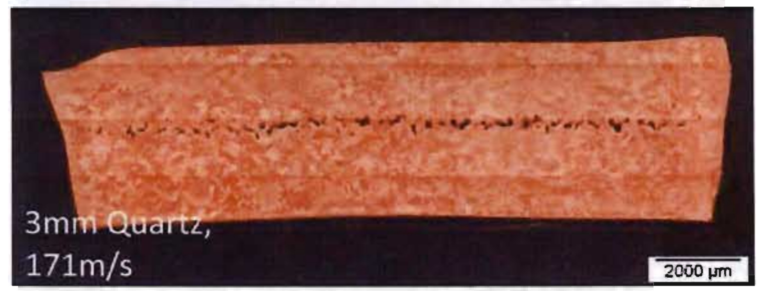
Koller and Cerreta, *APS SCCM Proceedings*, 2005.

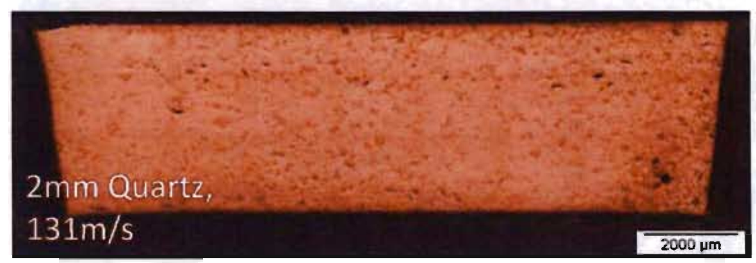
Hypothesis: kinetic and spatial parameters have an important role in dynamic damage evolution

Scoping Calculations and Determination of Early Stage Damage

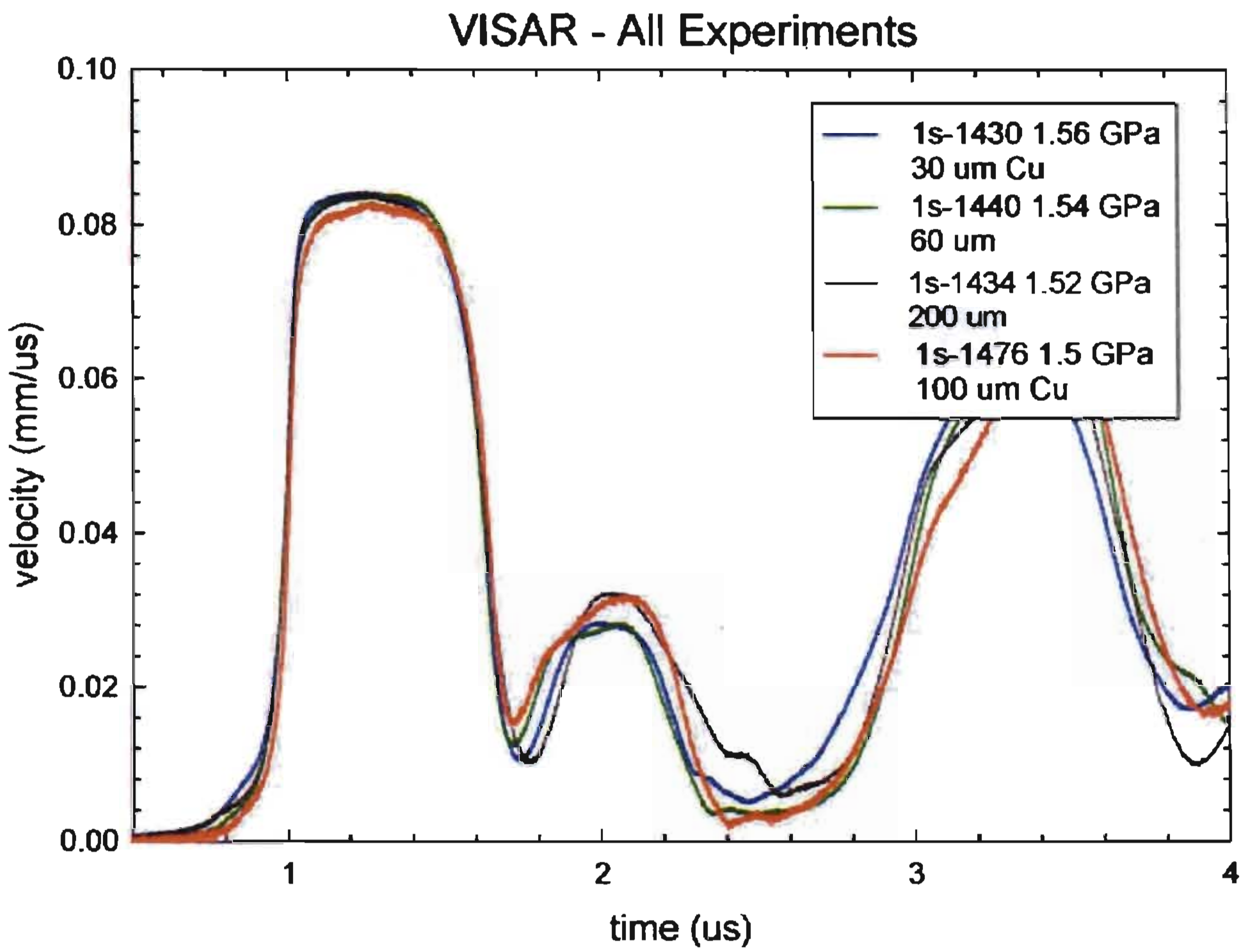




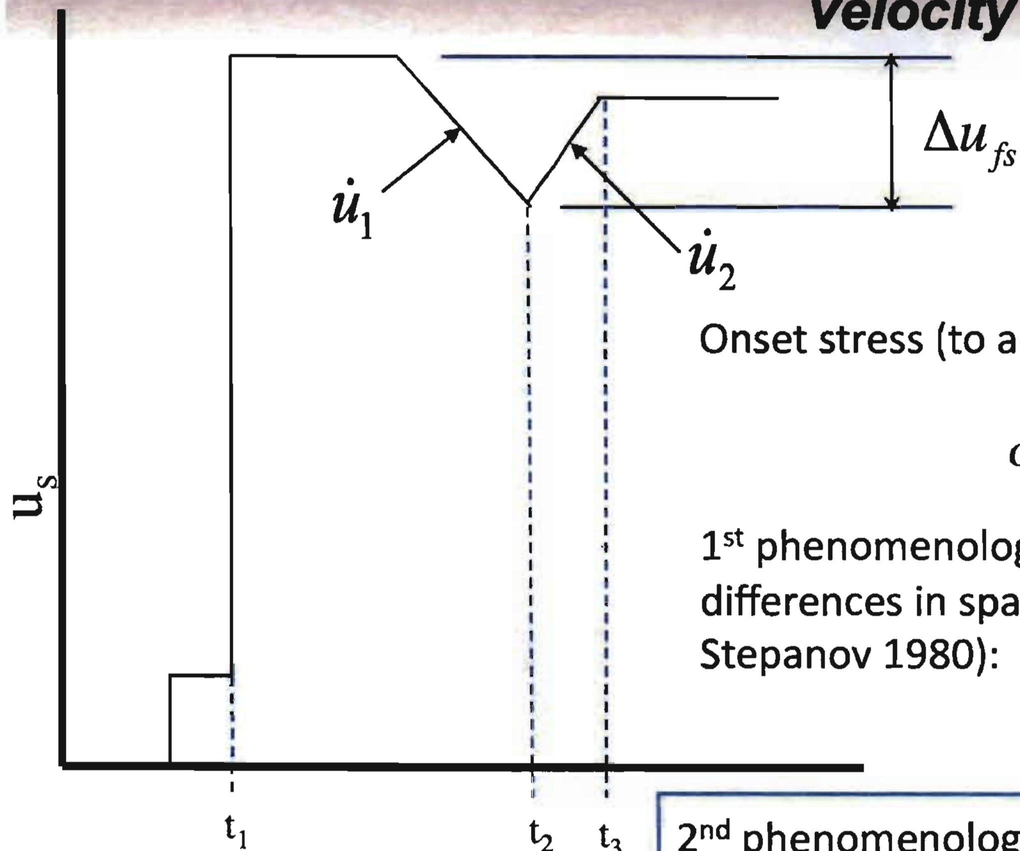




Identical loading conditions yield similar VISAR results for 4 grain sizes.



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



Spall strength (acoustic approach linear approx. Novikov 1966) :

$$\sigma \approx \frac{1}{2}\rho_0 C_0 \Delta u_{fs}$$

Onset stress (to account for el-pl behavior Stepanov 1976):

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

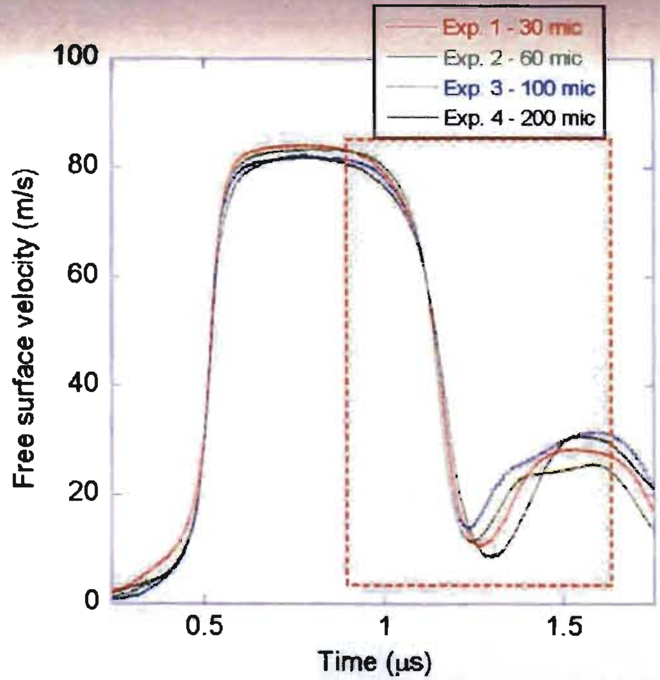
1st phenomenological correction factor (to compensate for differences in spall plate thickness Romanchenko and Stepanov 1980):

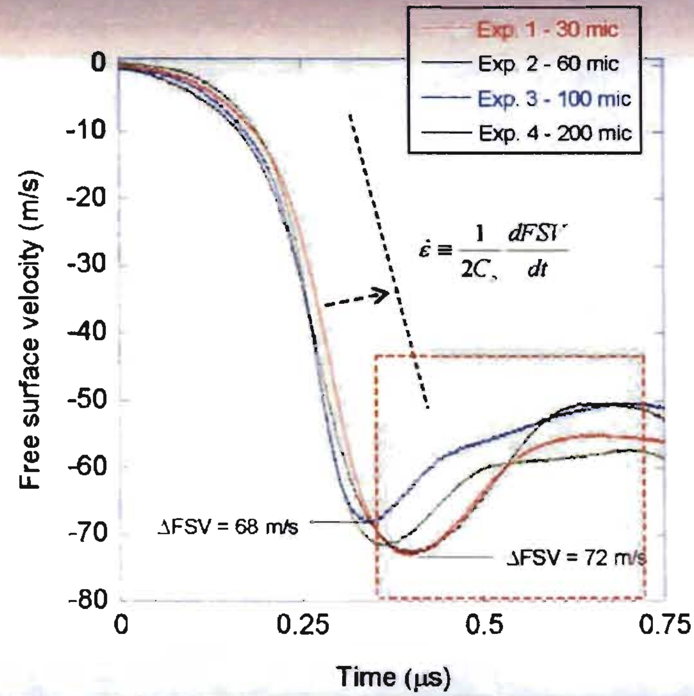
$$\Delta\sigma = \frac{1}{2}\frac{d\sigma}{dt}\bigg|_{C} h_s \cdot \left(\frac{1}{C_B}-\frac{1}{C_L}\right)$$

2nd phenomenological correction factor (correction for distortion due to el-pl properties of material. Kanel 1984):

$$\delta = \left(\frac{h_s}{C_B}-\frac{h_s}{C_L}\right)\frac{\left|\dot{u}_1\,\dot{u}_2\right|}{\left|\dot{u}_1\right|+\dot{u}_2}$$

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

Curran, Seaman, Shockey, and co-workers developed NAG theories between 71-81

Defines a nucleation rate:

$$\dot{N} = \dot{N}_0 \exp\left[\frac{(\sigma - \sigma_{n0})}{\sigma_1}\right]$$

Defines a growth rate

$$\dot{R} = \left(\frac{\sigma - \sigma_{g0}}{4\eta}\right) R$$

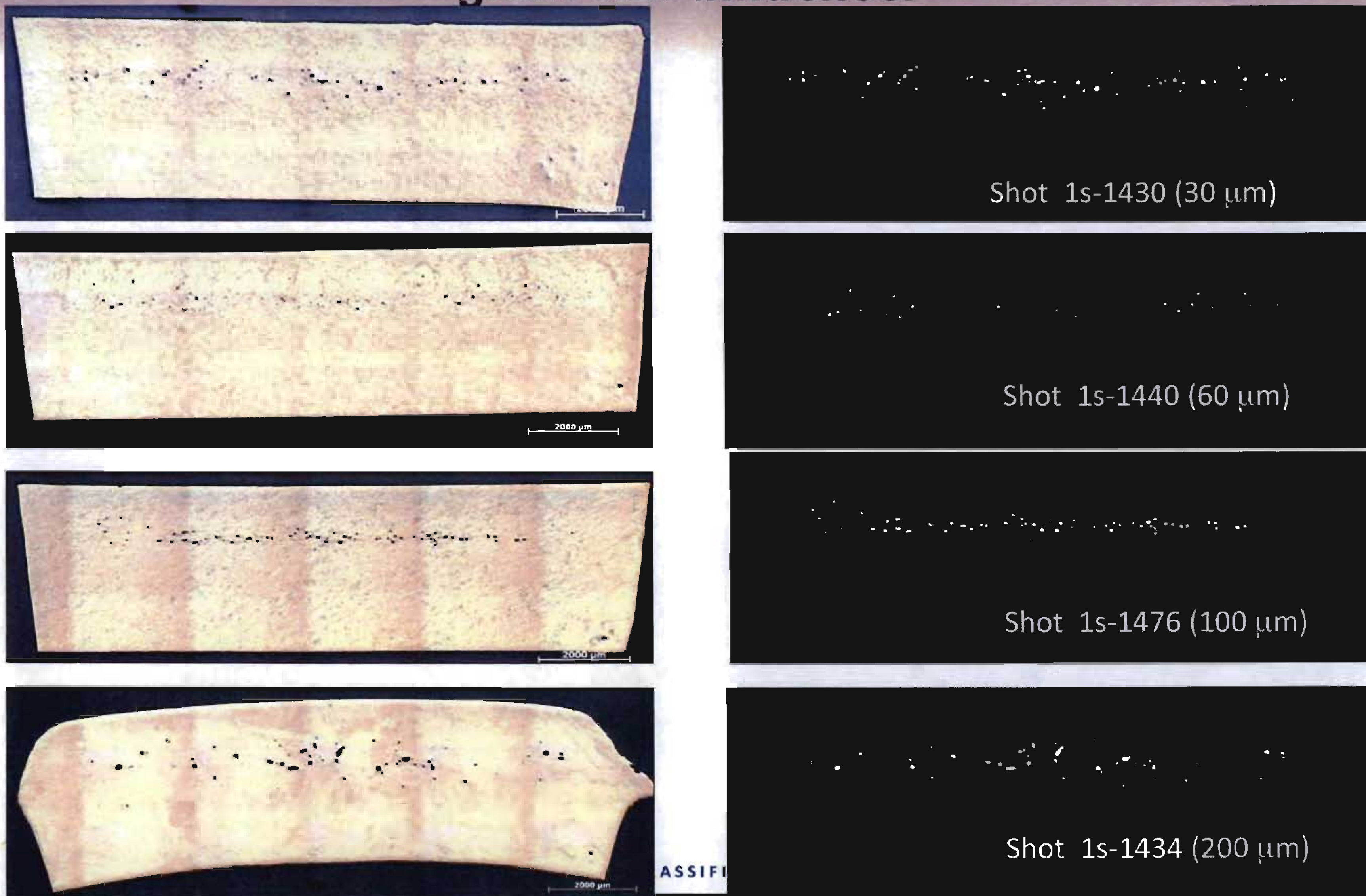
Nucleation may not be an instantaneous process, but the changing conditions over an affected volume may allow nucleation and growth to occur simultaneously for some time.

We need models like this that incorporate the plastic flow and microstructural effects.

See work by Lebensohn for new model tracking triaxiality of stress states which leads to conditions that allow some voids to continue to grow and others to stagnate.

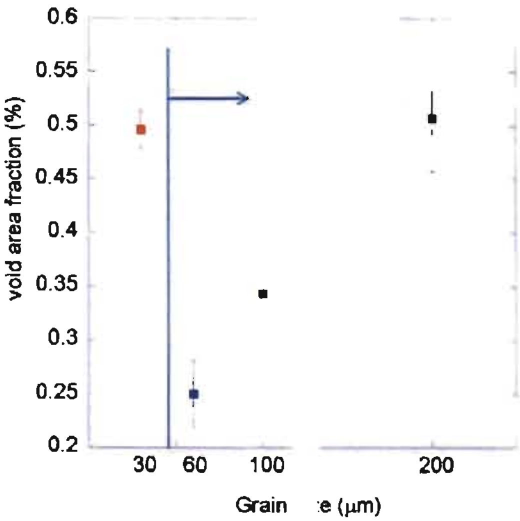
[1] R.A. Lebensohn, M.I. Idiart, P. Ponte Castañeda and P.G. Vincent:"Dilatational viscoplasticity of polycrystalline solids with intergranularcavities". Philosophical Magazine, in press.
[2] R.A. Lebensohn: "Modeling ductile damage of polycrystallinematerials". Keynote Lecture, IUTAM Symposium on Linking Scales inComputations: from Microstructure to Macro-scale Properties, Pensacola,FL, USA, May 2011.

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

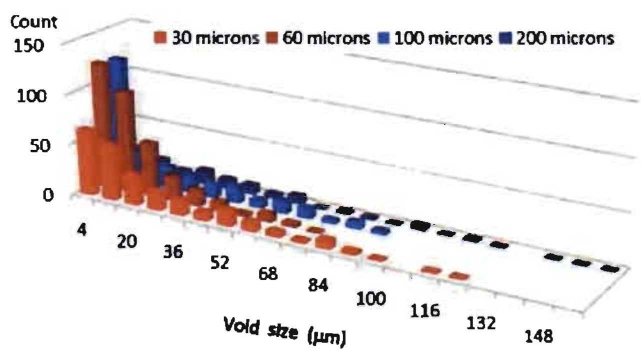


ASSIFI

Void area fraction does not follow a linear trend.



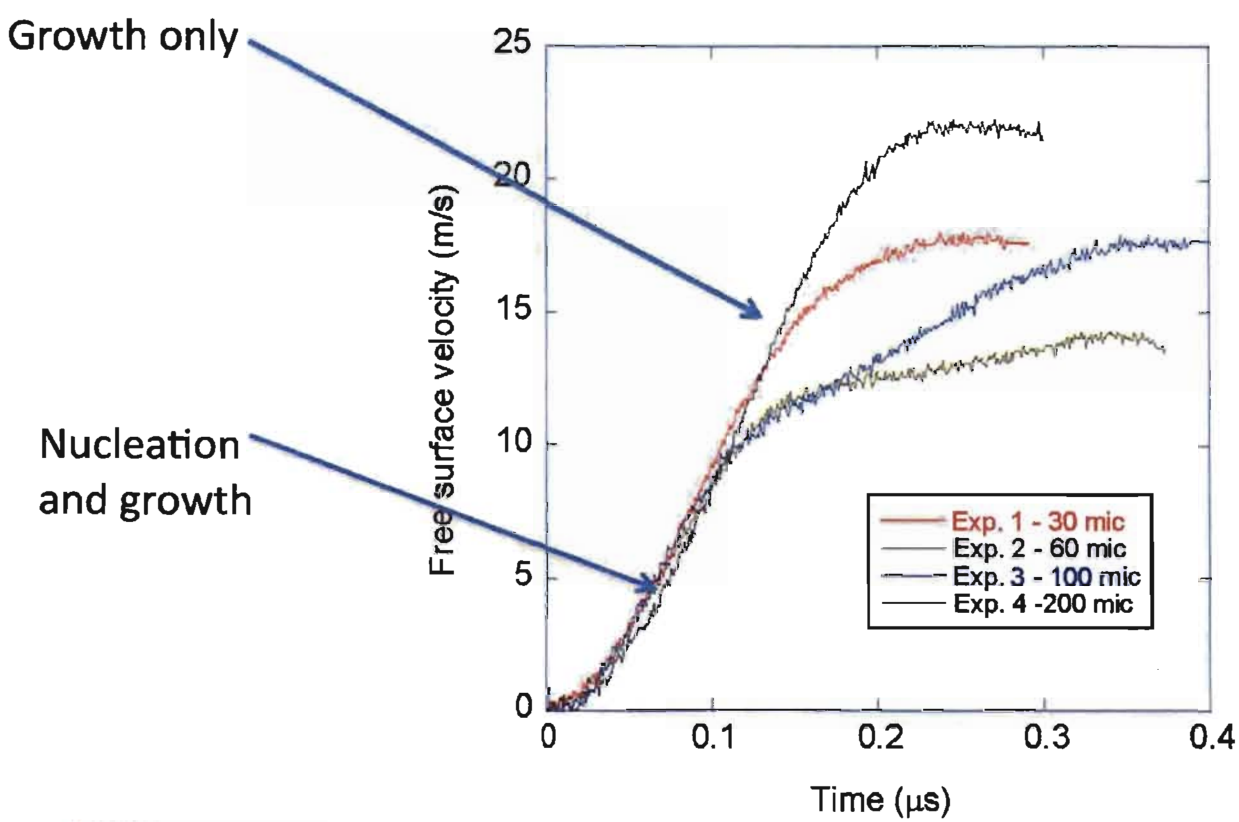
(a)



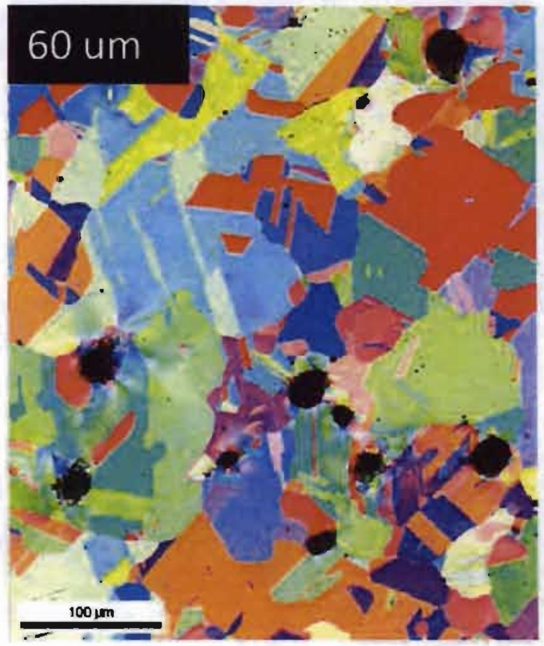
(b)

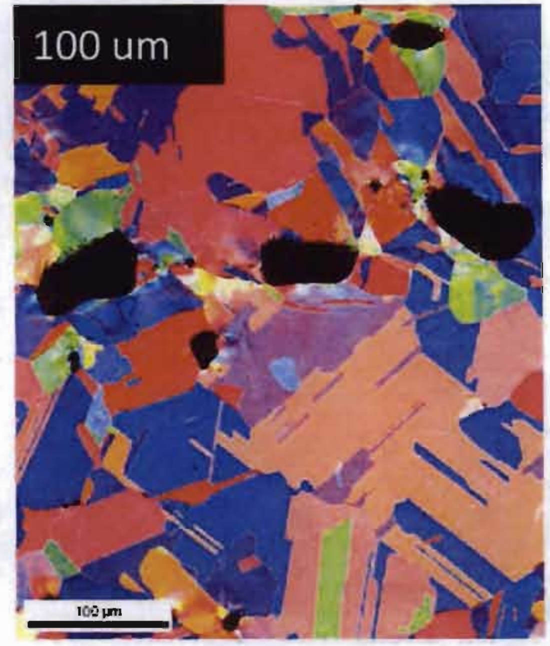
Fig. 6 (a) Void area fraction as function of the grain size. (b) void size distribution.

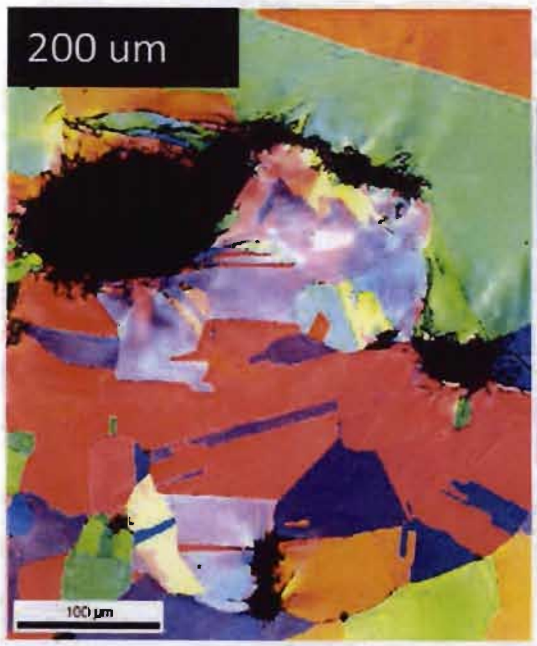
VISAR results show the difference between a slower rate growth process of individual voids and the faster process of ***coalescence.***



Mechanisms are additive and give rise to a cumulative damage rate which is dependent on triaxiality of stress state, and defect distribution under tensile load.







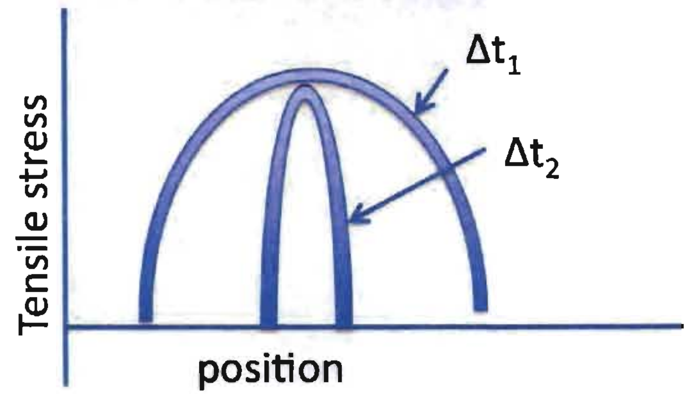
Damage Statistics from 2D optical analysis

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

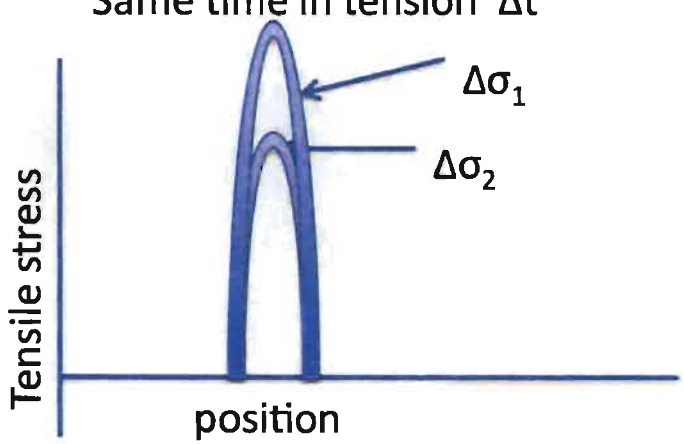
Ongoing work

Using simple wave interaction calculations (without damage models). We are designing experiments to probe the evolution of the tensile pulse and its effect on damage state.

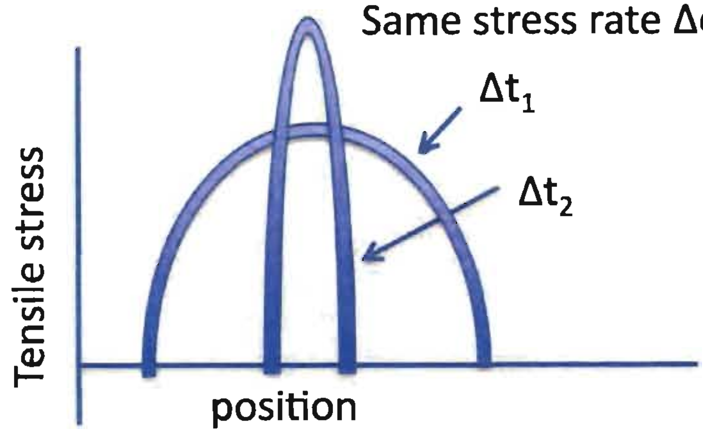
Same peak stress σ



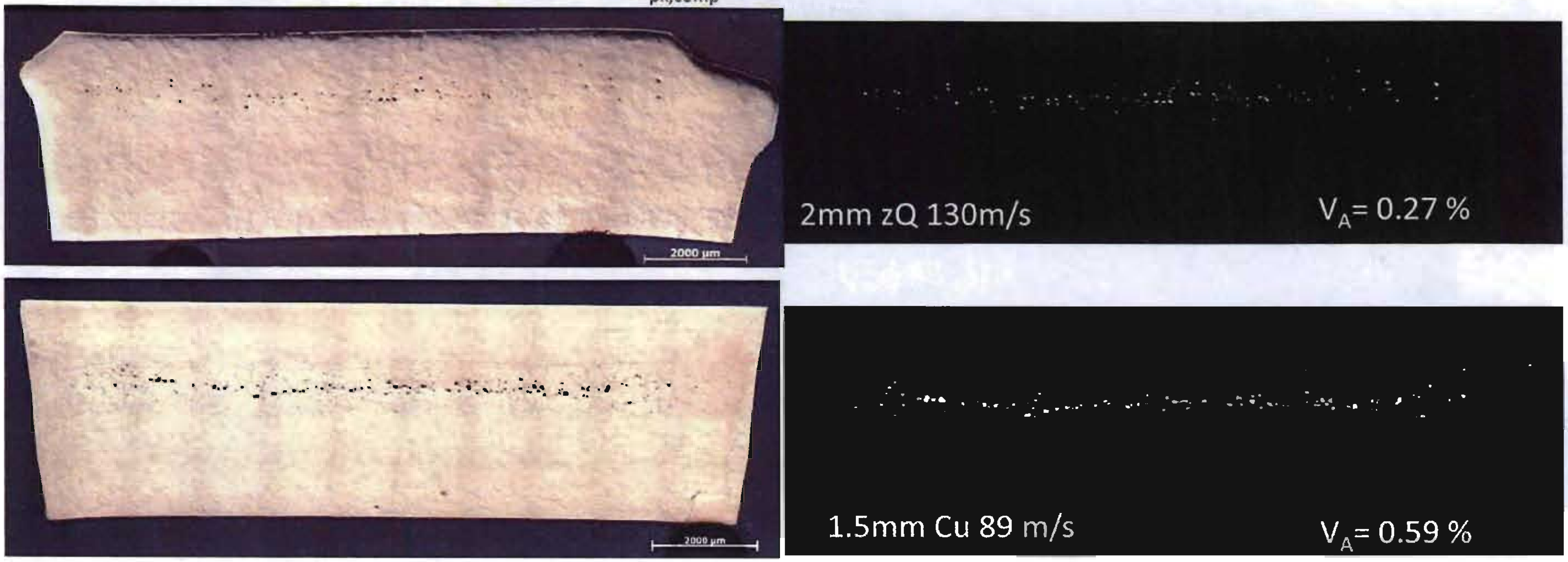
Same time in tension Δt



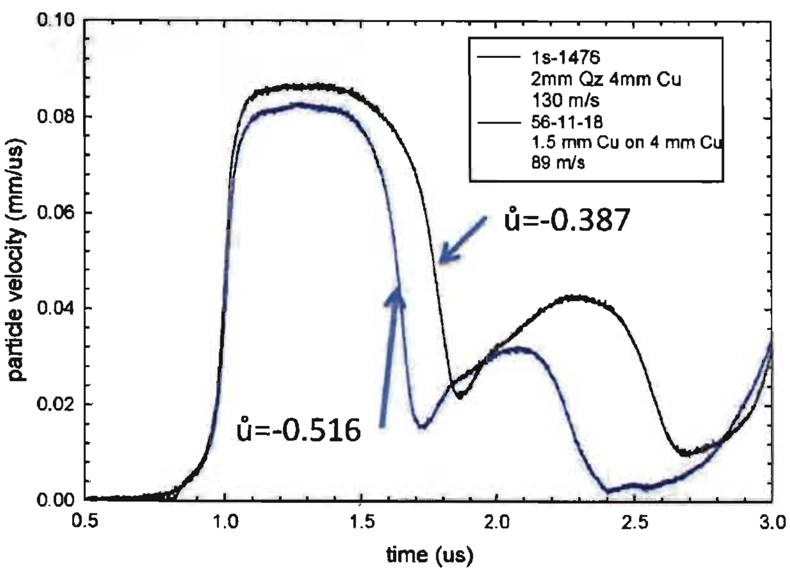
Same stress rate Δσ/Δt



$\sigma_{pk,comp}$ = ~ 1.5 GPa



VISAR comparison for tensile pulse rate study



Qz tensile rate 8% smaller/slower

Qz delta x 46% larger (same grain size)

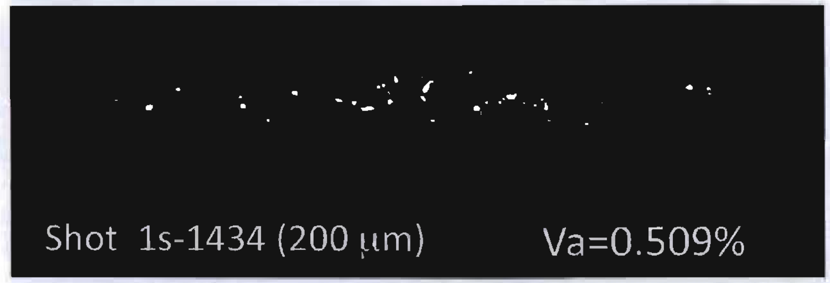
dx/dt2 36% faster

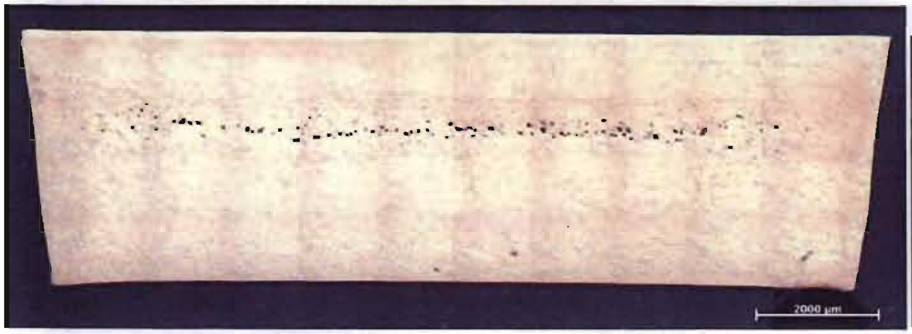
Qz peak tension 26% higher

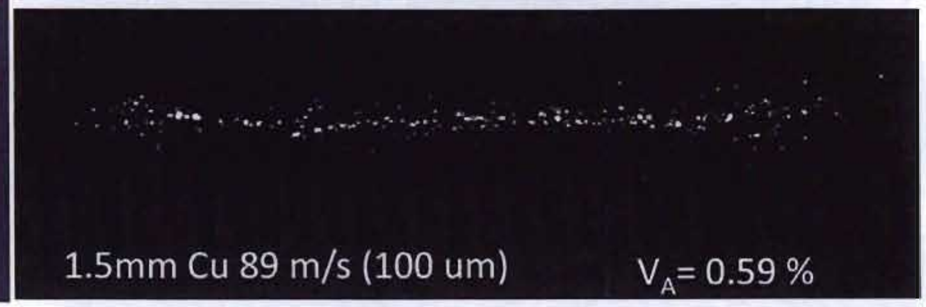
Qz pulse duration flat top

Results in Qz ů 33% steeper/faster

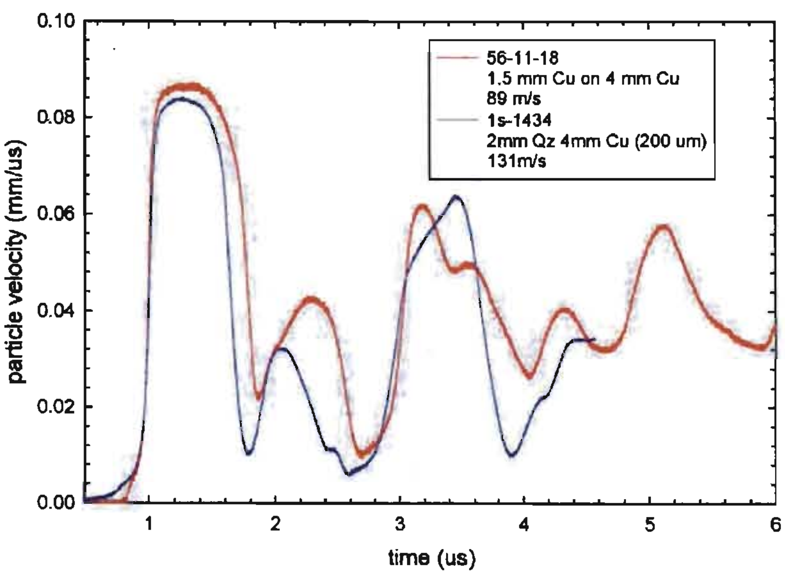
And Qz Va 0.32% lower







VISAR comparison for tensile pulse rate study



Qz tensile rate 8% smaller/slower

Qz delta x 46% larger (grain size 100% larger)

dx/dt2 36% faster

Qz peak tension 26% higher

Qz pulse duration flat top

Results in Qz ů ~ same

And Qz Va 0.08% lower

Summary of Strength and Damage in metals 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 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.