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Title: The effects of shockwave profile shape and shock obliquity on spallation in Cu and Ta: kinetic and stress-state effects on damage evolution

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The effects of shockwave profile shape and shock obliquity on spallation in Cu and Ta: kinetic and stress-state effects on damage evolution

George T. (Rusty) Gray III

Los Alamos National Laboratory

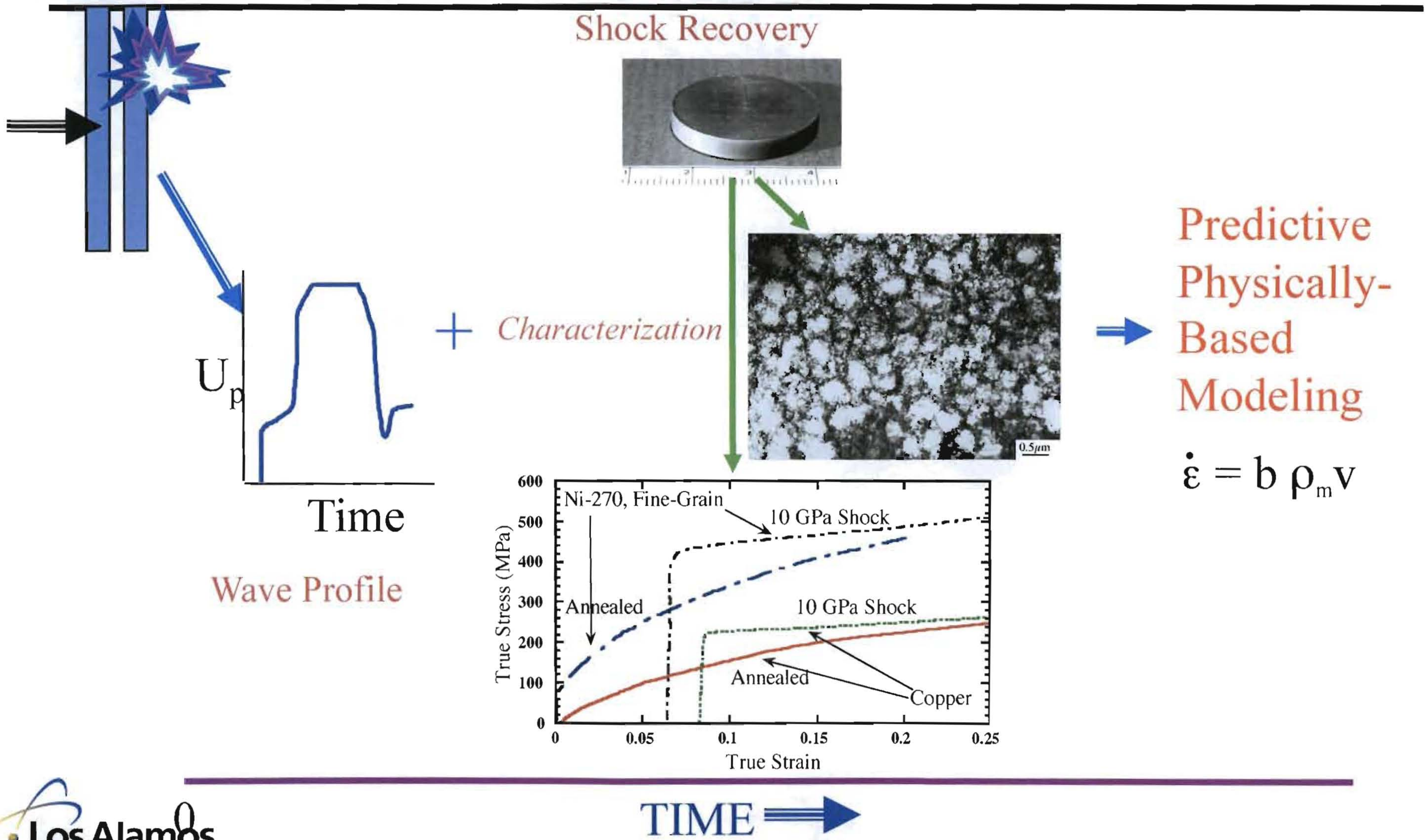
Widespread research over the past five decades has provided a wealth of experimental data and insight concerning shock hardening and the spallation response of materials subjected to square-topped shock-wave loading profiles. Less quantitative data have been gathered on the effect of direct, in-contact, high explosive (HE)-driven Taylor wave (or triangular-wave) loading profile shock loading on the shock hardening, damage evolution, or spallation response of materials. Explosive loading induces an impulse dubbed a "Taylor Wave". This is a significantly different loading history than that achieved by a square-topped impulse in terms of both the pulse duration at a fixed peak pressure, and a different unloading strain rate from the peak Hugoniot state achieved. The goal of this research is to quantify the influence of shockwave obliquity on the spallation response of copper and tantalum by subjecting plates of each material to HE-driven sweeping detonation-wave loading and quantify both the wave propagation and the post-mortem damage evolution. This talk will summarize our current understanding of damage evolution during sweeping detonation-wave spallation loading in Cu and Ta and show comparisons to modeling simulations. The spallation responses of Cu and Ta are both shown to be critically dependent on the shockwave profile and the stress-state of the shock. Based on variations in the specifics of the shock drive (pulse shape, peak stress, shock obliquity) and sample geometry in Cu and Ta, "spall strength" varies by over a factor of two and the details of the mechanisms of the damage evolution is seen to vary. Simplistic models of spallation, such as P_{min} based on 1-D square-top shock data lack the physics to capture the influence of kinetics on damage evolution such as that operative during sweeping detonation loading. Such considerations are important for the development of predictive models of damage evolution and spallation in metals and alloys.

The effects of shockwave profile shape and shock obliquity on spallation in Cu and Ta: kinetic and stress-state effects on damage evolution

George T. (Rusty) Gray III

LA-UR-10-

Investigation of shock loading: a question of time



Shock Recovery Experiments - A Window into Shock Prestraining

- Evolved from C.S. Smith Experiments with GMX6 of LANL (1958) on recovery techniques for shocked materials

•Question: Given that the shock-loading process is a high-rate loading (risetime) / hold (duration) / and unloading (release) cycle ---

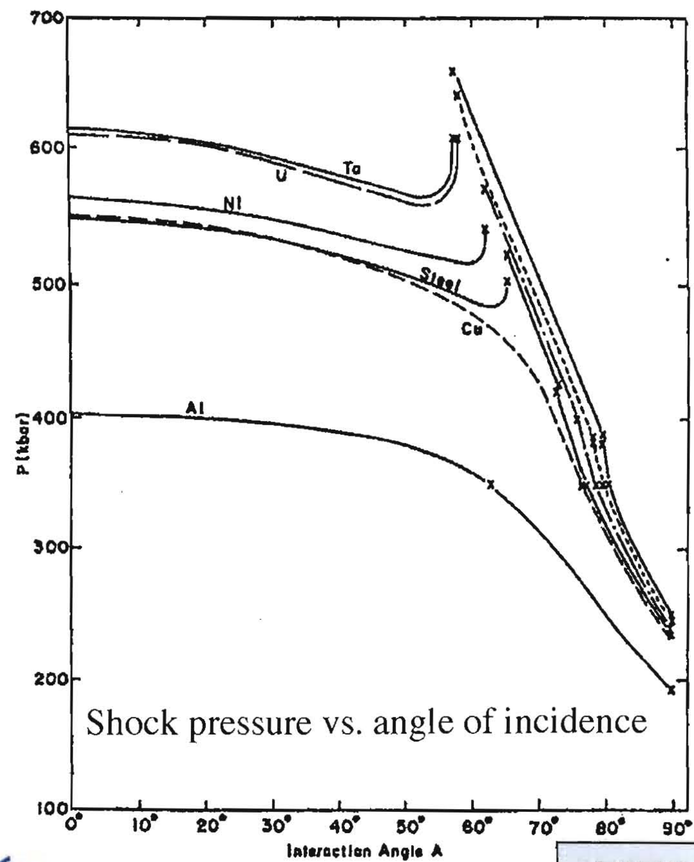
•How are defects generated and stored in each phase and how does this process differ between materials?

Oblique Detonation Waves

……One way of introducing shear is through single-point initiated det wave.

Shear component is function of t and position, although P still dominant at high obliquity.

Example of explosively loaded flat disc



J.W. Walsh
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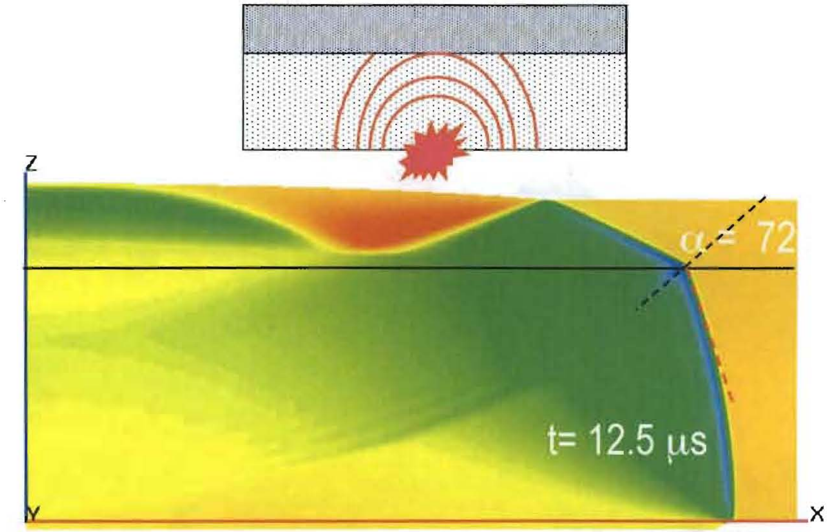


CJ pressure for PBX 9501

T. A. Mason

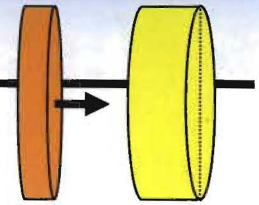
Four Regimes Possible: just consider this from here on

1. *Regular reflection (0 – 58 degrees)*
2. Mach reflection (58 – 78 degrees)
3. Regular with multiple metal shocks (78- 79)
4. Regular with product rarefaction (79 - 90)

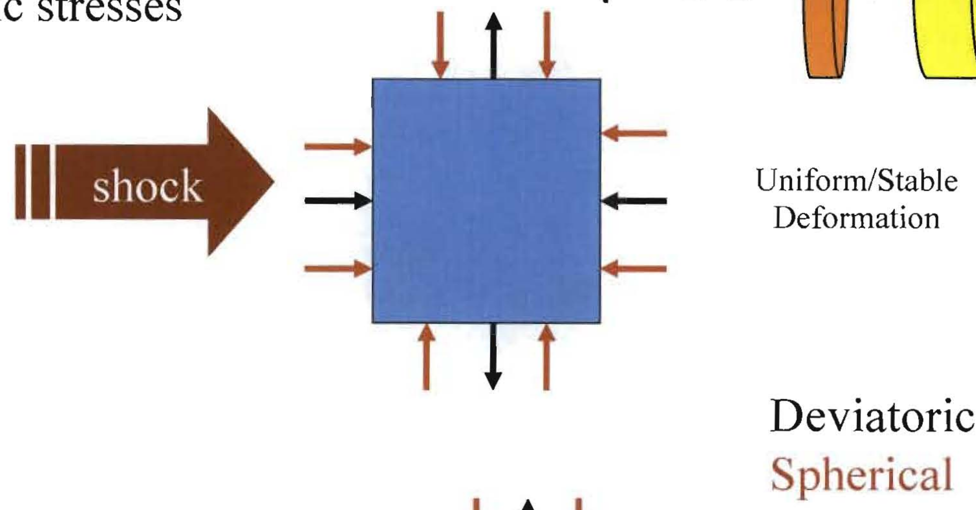
Strong Shock Loading

- Normal 1D shock compression/release
- Superimposed spherical & deviatoric stresses (loosely uncoupled)

$$P >> \sqrt{3/2\, \underline{\underline{s}} : \underline{\underline{s}}}$$

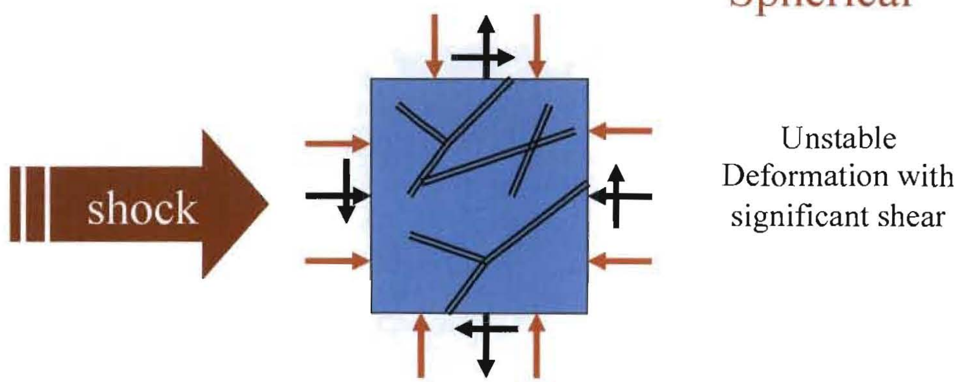


$$\underline{\underline{\sigma}} = \begin{pmatrix} s_{11} - P & 0 & 0 \\ & s_{22} - P & 0 \\ & & s_{33} - P \end{pmatrix}$$



$$\underline{\underline{\varepsilon}} = \begin{pmatrix} e_{11} + 1/3\,\varepsilon_v & 0 & 0 \\ & e_{22} + 1/3\,\varepsilon_v & 0 \\ & & e_{33} + 1/3\,\varepsilon_v \end{pmatrix}$$

$$\underline{\underline{\varepsilon}} = \begin{pmatrix} e_{11} + 1/3\,\varepsilon_v & e_{12} & e_{13} \\ & e_{22} + 1/3\,\varepsilon_v & e_{23} \\ & & e_{33} + 1/3\,\varepsilon_v \end{pmatrix}$$

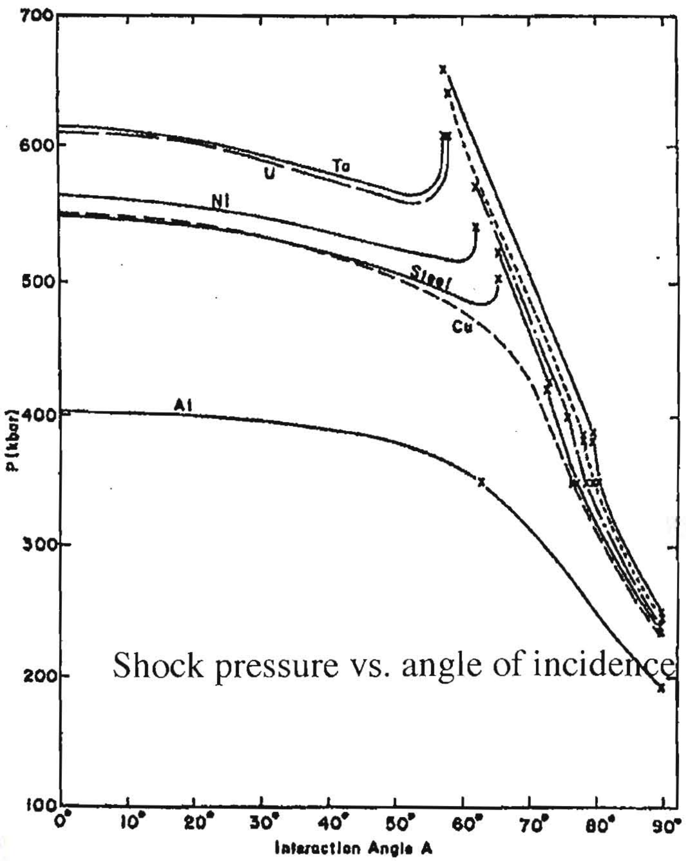


Shear component may lead to localization/fracture in the wake of the shock!
What can produce a significant shear component (significant wrt P)?.....

Oblique Detonation Waves

......One way of introducing shear is through single-point initiated det wave. Shear component is function of t and position, although P still dominant at high obliquity.

Example of explosively loaded flat disc



Shock pressure vs. angle of incidence

Four Regimes Possible:

1. *Regular reflection (0 – 58 degrees)*
2. Mach reflection (58 – 78 degrees)
3. Regular with multiple metal shocks (78- 79)
4. Regular with product rarefaction (79 - 90)

J.W. Walsh
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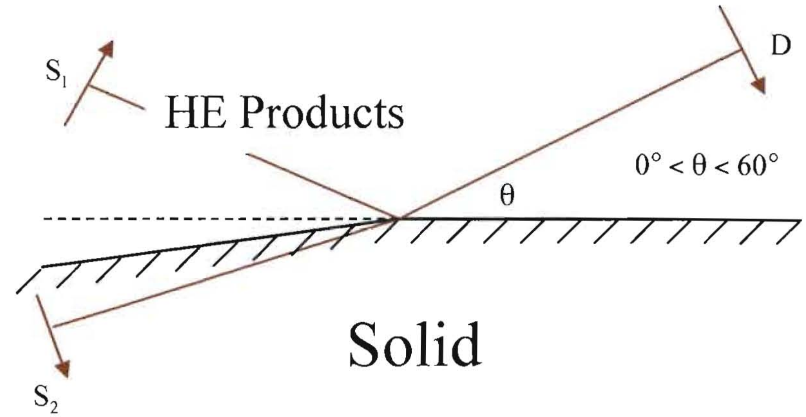
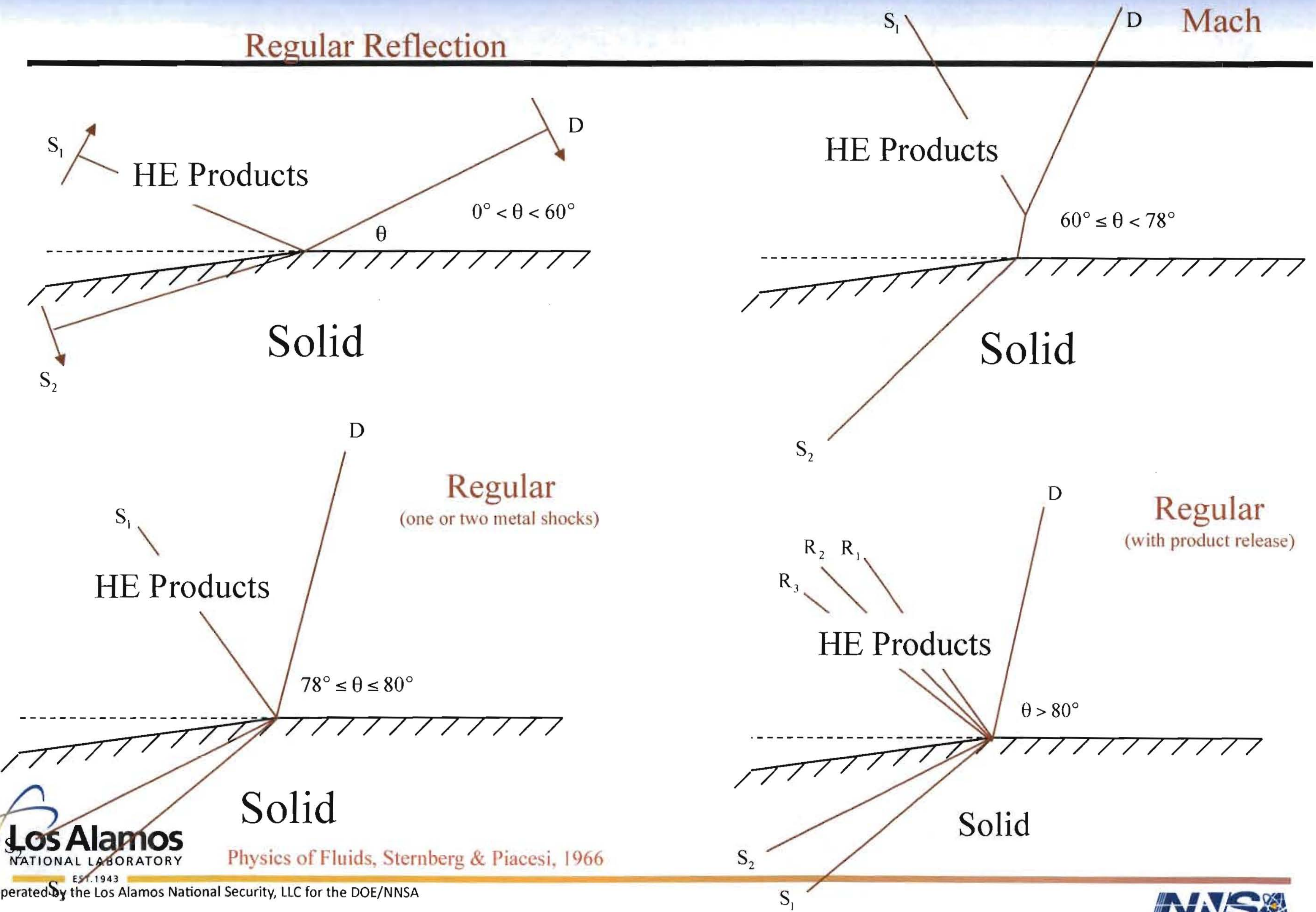


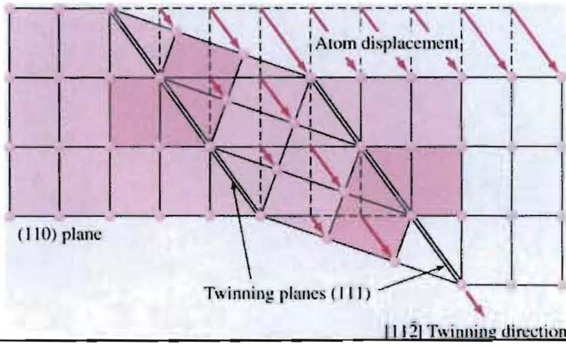
Oblique Reflection Wave Structures

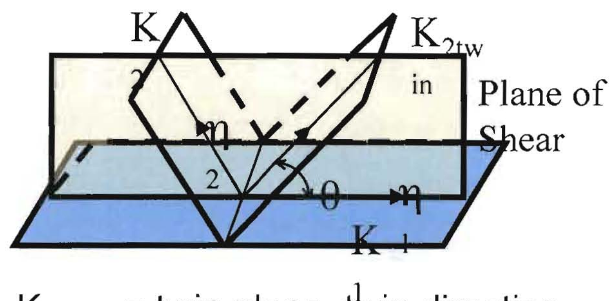


Physics of Fluids, Sternberg & Piacesi, 1966

Deformation Twinning

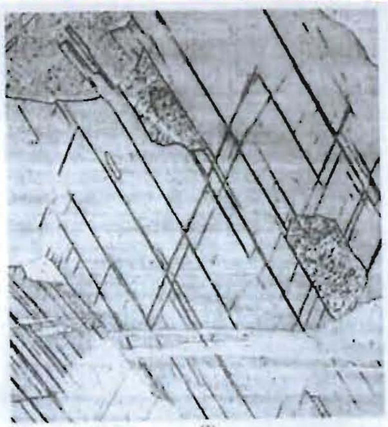
Twin initiation or growth occurs when the externally applied shear stress across the K_1 plane, resolved in the ω_1 direction, reaches a "critical" value.





K_1, η_1 = twin plane, twin direction

- **Twins in most crystal structures form more readily as the temperature of deformation is decreased or the rate of deformation is increased.**



(b)

(b) Same as Fig. 5, another field. X500.

Fig. 13—Microstructure of annealed α brass (31.40 pct Zn) after 550-kbar shock. X250.

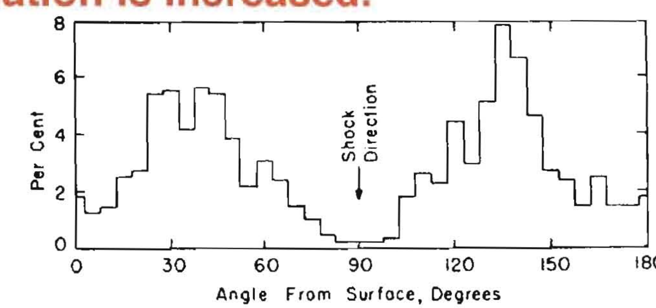


Fig. 14—Angular frequencies of markings on brass after 550-kbar normal shock. Plane of section includes shock direction.

C.S. Smith: Trans. AIME (1958)

Twinning during shock loading: A complex series of differing observations

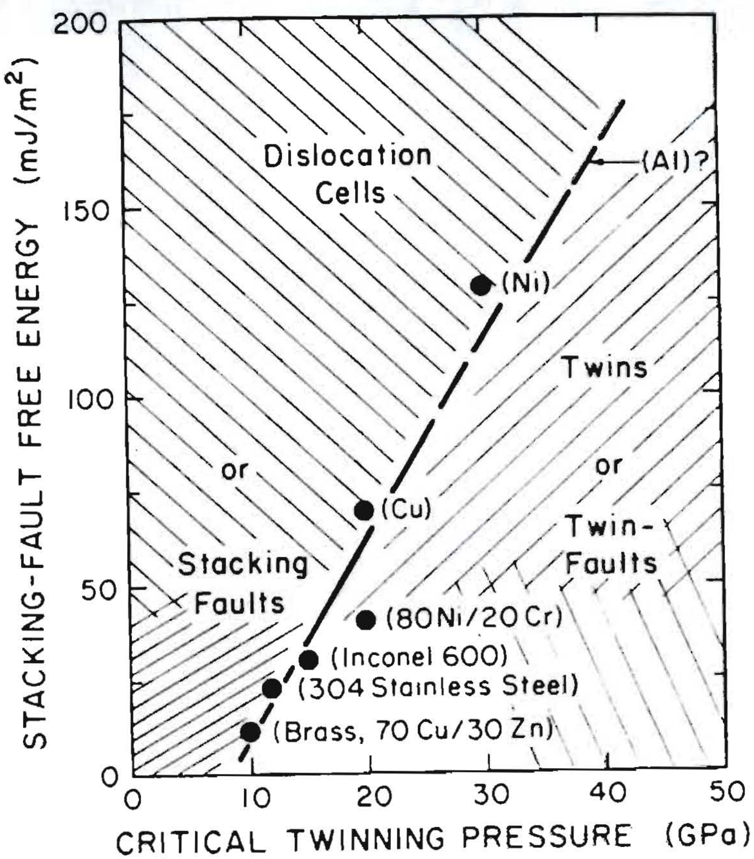


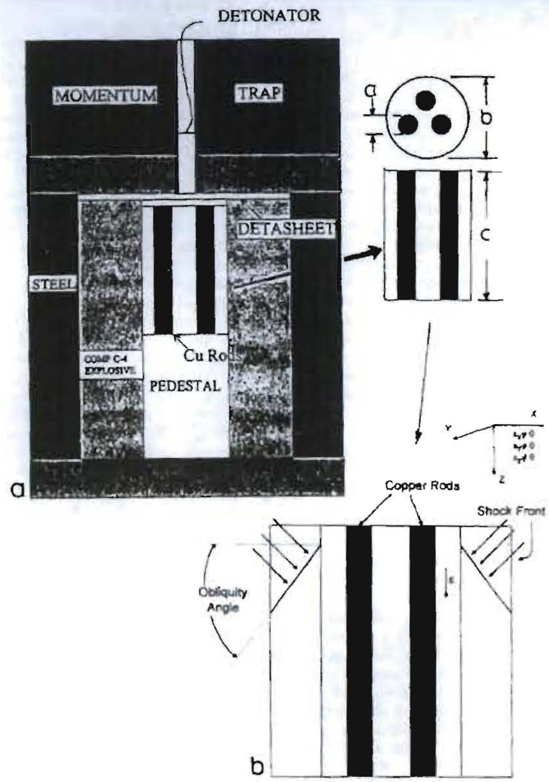
FIG. 1.15: *Stacking-fault free energy versus critical twinning pressure (for initial twinning in [001] directions) for a number of FCC metals and alloys where the residual strains were very small or negligible (<1%), and $\Delta t = 2\mu s$, i.e. the shock pulse duration shown in Fig. 1.7 was constant at 2 microseconds). The shaded regimes illustrate the approximate, residual microstructures or classes of microstructures which are dominant (from reference 17).*

L.E. Murr, APS Topical Conf. Proceedings (1987).

Murr & Staudhammer: Shock Waves for Industrial Applications: (1988):

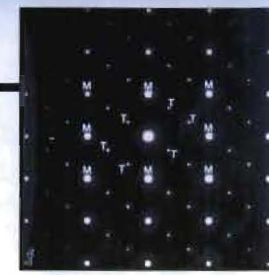
1-D Shock Loading - Generalized prediction of critical twinning shock stress

Twinning during shock loading: A complex series of differing observations in Cu & Ta observations



Sanchez, Murr & Staudhammer: Acta Mater., (1997), vol. 45, pp. 3223-3235.

"The obliquity of the shock wave seems to suppress the critical shock pressure of copper, since twinning was observed at pressures of only 11 GPa at the top of the rods in contrast to an established critical twinning pressure of ~ 20 GPa for plane-wave loaded Cu."



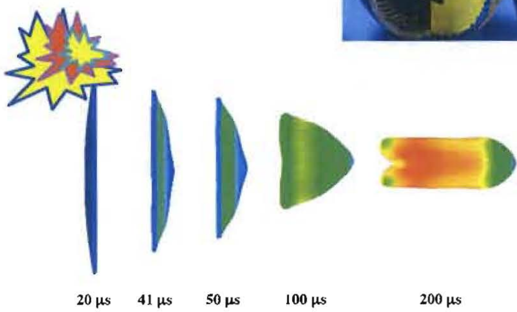
Gray & Vecchio: Metall. Trans. (1995)

Deformation twins in Ta-10W shocked at 20GPa

Pappu, Kennedy, Murr & Meyers: Scripta Mater., (1996), vol. 35, pp. 959-965.

"There was no evidence of these features in any of the Ta EFP's. Since shock-waves of higher peak pressures than necessary for plane-wave shock induced twinning are involved in EFP formation it is believed that the actual, dynamic deformation process either retards or annihilates deformation twins."

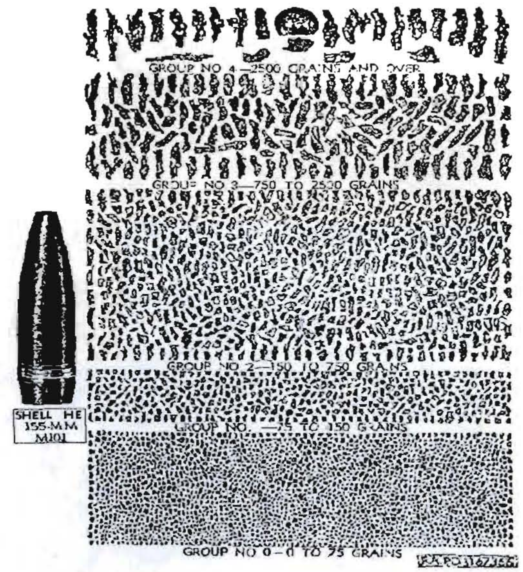
Effect of HE-Shock Driven Shock Prestraining on Materials



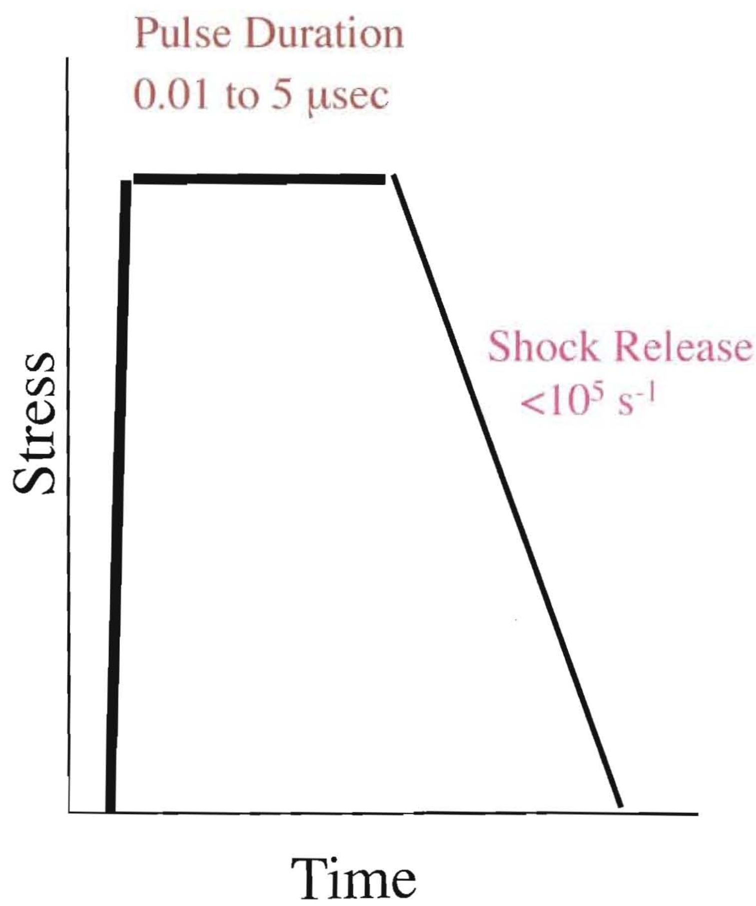
Constitutive Response of Warheads / weapon materials are preconditioned by HE preshock load cycle.

Predictive Performance of Warhead requires knowledge of shock hardening

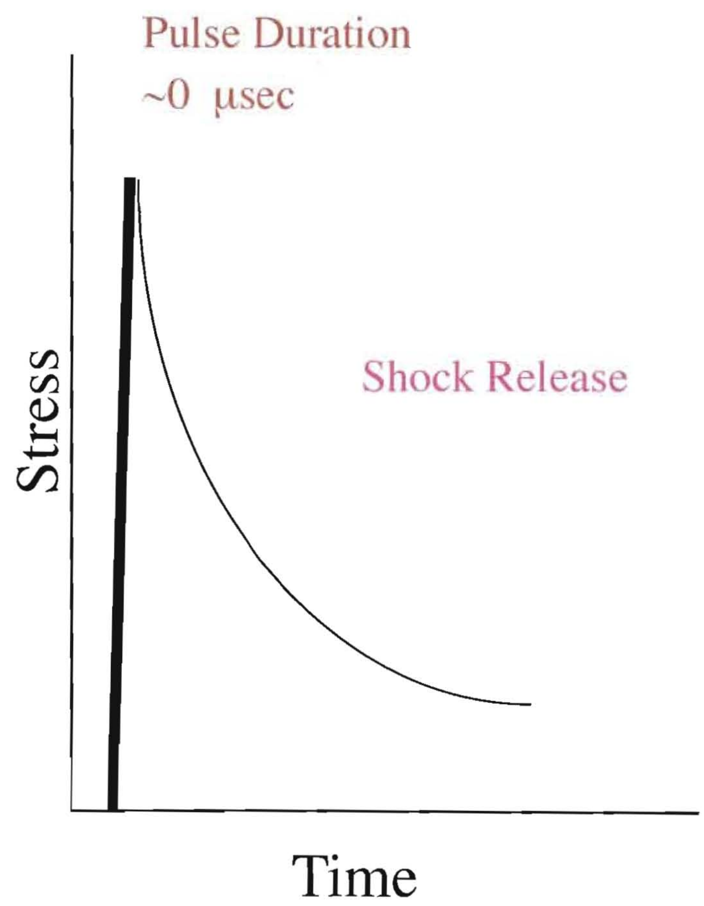
Liners / warheads



Shock-Wave Prestrain - Flyer Plate vs. Taylor Wave



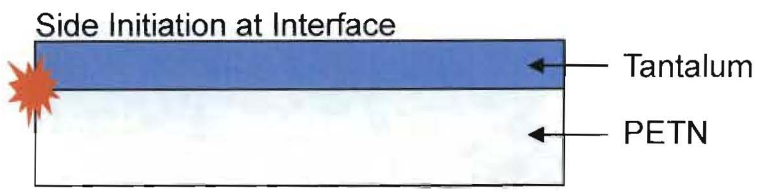
Flyer-Plate

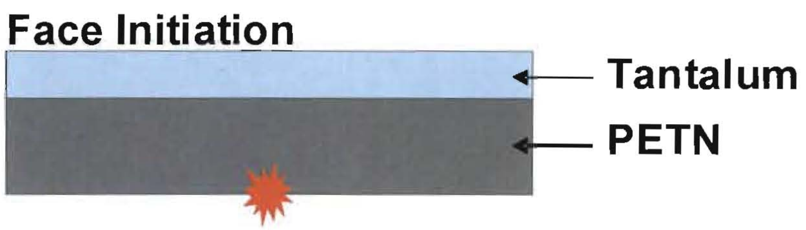


Energetic-Taylor Wave

Experimental Set-Up

- *Tantalum Cylinder 1217B , Ø8mm, 4.47mm thick*
- *PETN pellet Ø8mm, 2mm thick, 1.55g/cc*
- *High voltage slapper foil initiation*
- *Test geometry:*



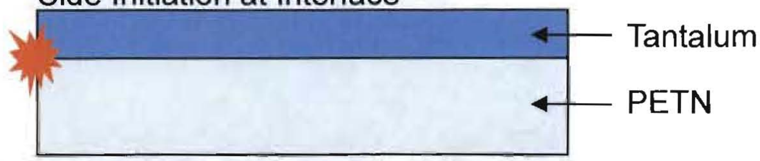


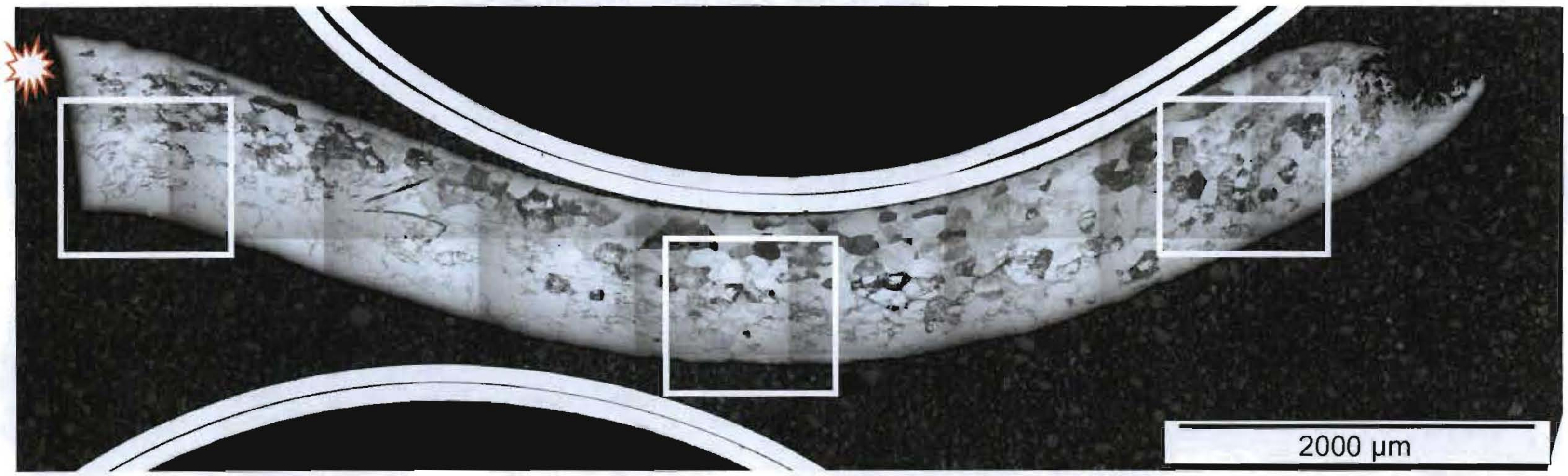
EBSD analysis:

- *5 scans selected in each region :*
  - *left bottom corner*
  - *center bottom corner*
  - *right bottom corner*
- *Scan size : 150 μm x 150 μm*
- *Scan step size: 0.15μm*

UPSET-FORGED Ta Specimen (UF-13)

Optical image @100x

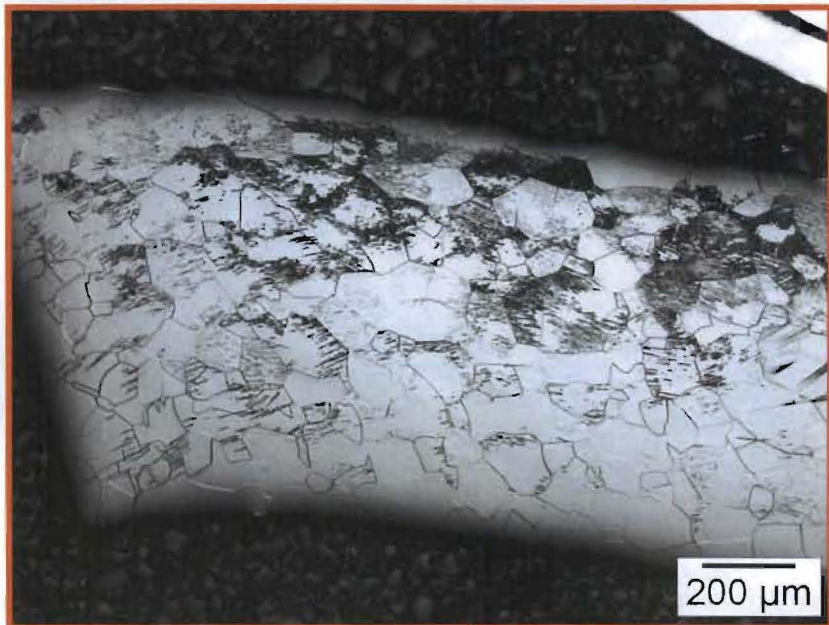




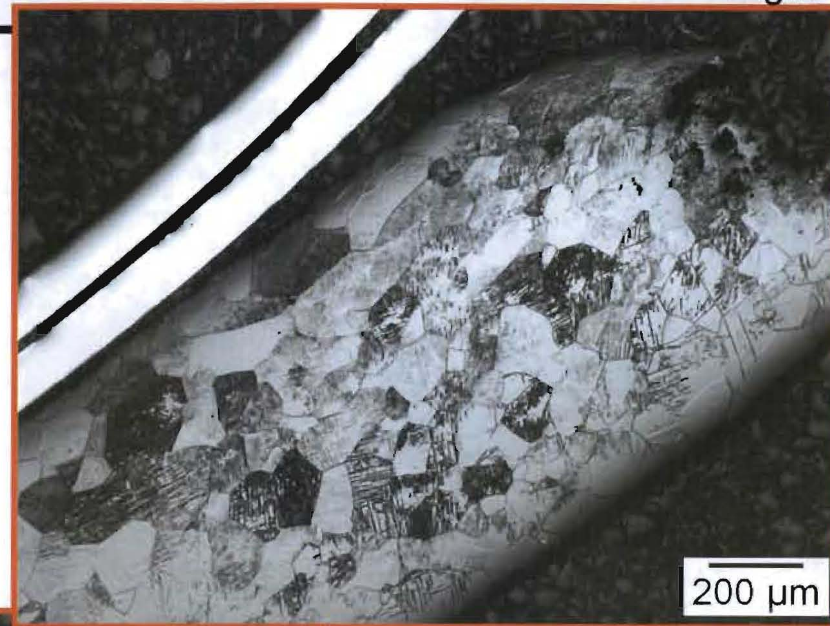
- Qualitatively, the amount of twinning increases from left to right, with a visibly higher concentration along the upper edge. (adjacent to HE)
- Red rectangles and twin close-up images are shown at larger scale on the next slide.

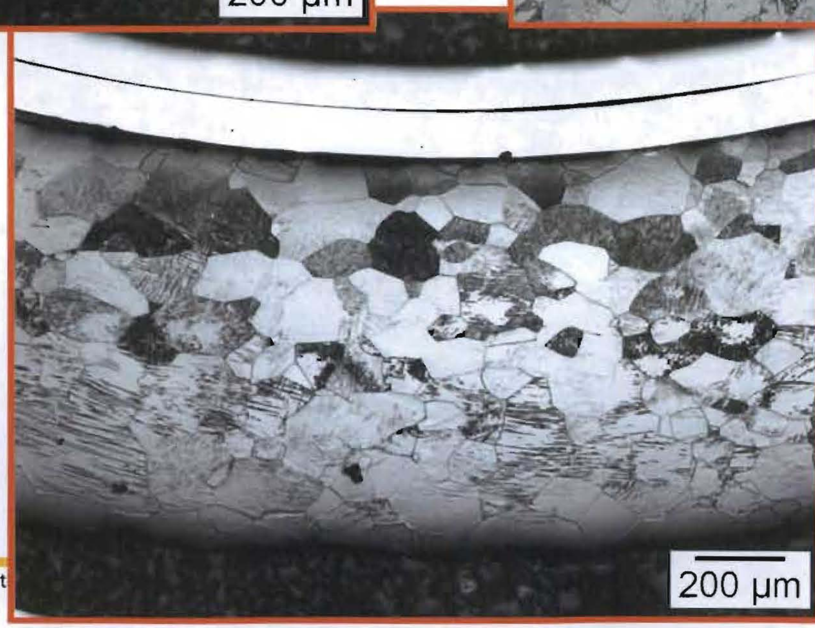
UPSET-FORGED Ta Specimen (UF-13)- *Optical Images*

Left



Right





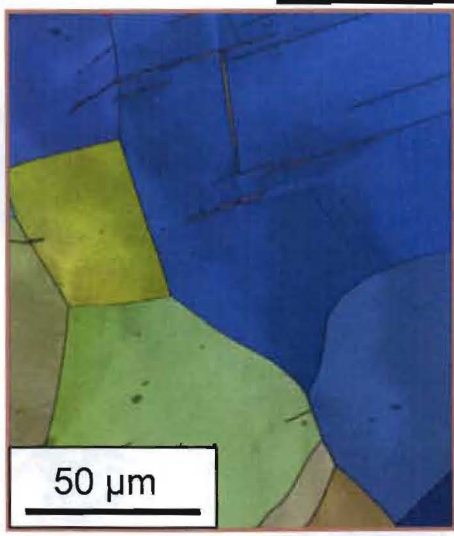
Center

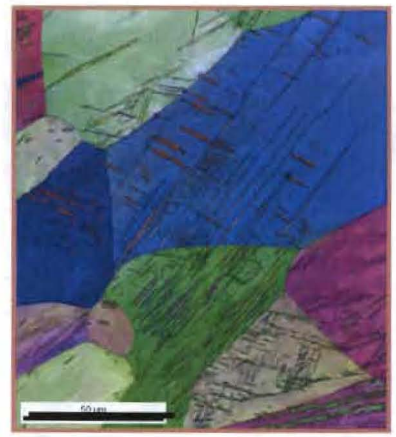
50 µm

UPSET-FORGED Ta Specimen (UF-13)- *EBSD data*

50 µm

	Bottom Left	Bottom Center	Bottom Right
Avg. twin fraction	0.21	0.47	0.52

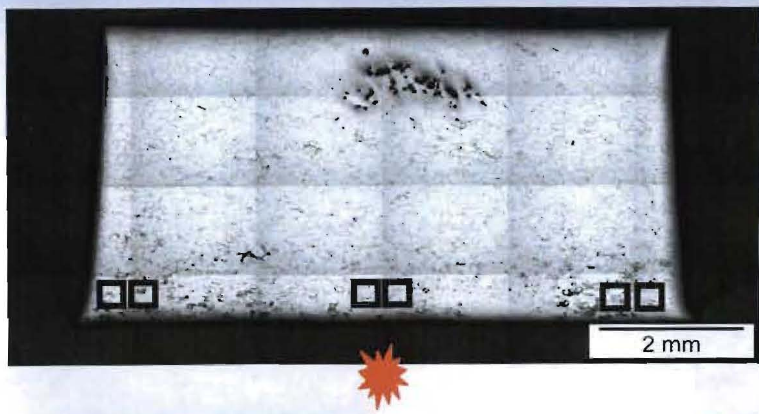




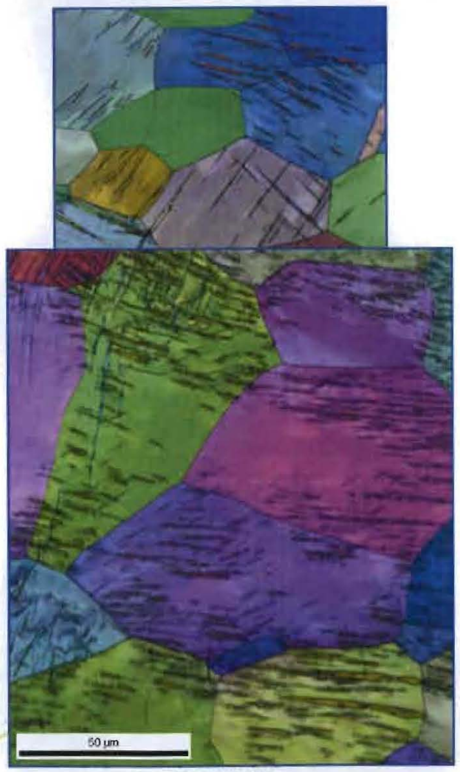
- Visually there are more twins in the center and right regions compared to the left region; EBSD confirms these observations

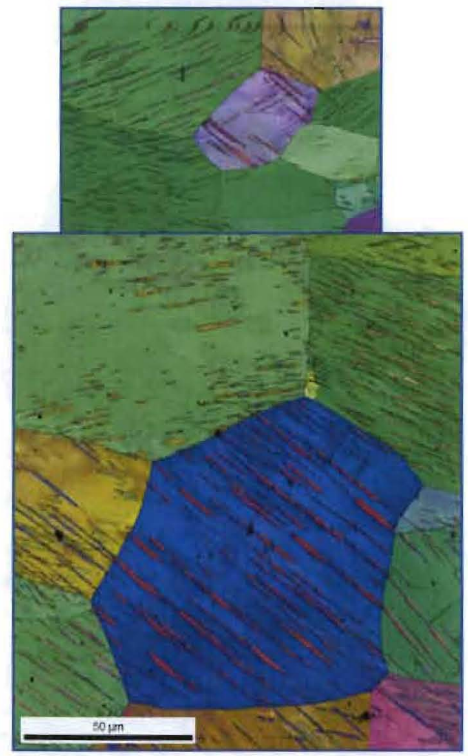
DOD/DOE Ta Specimen - *EBSD data*

Center Face Initiation



	Bottom Left	Bottom Center	Bottom Right
Avg. twin fraction	0.5	0.275	0.65

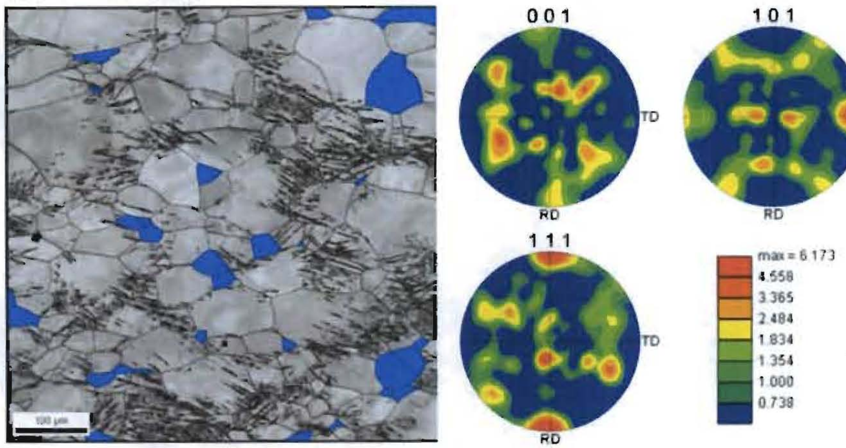




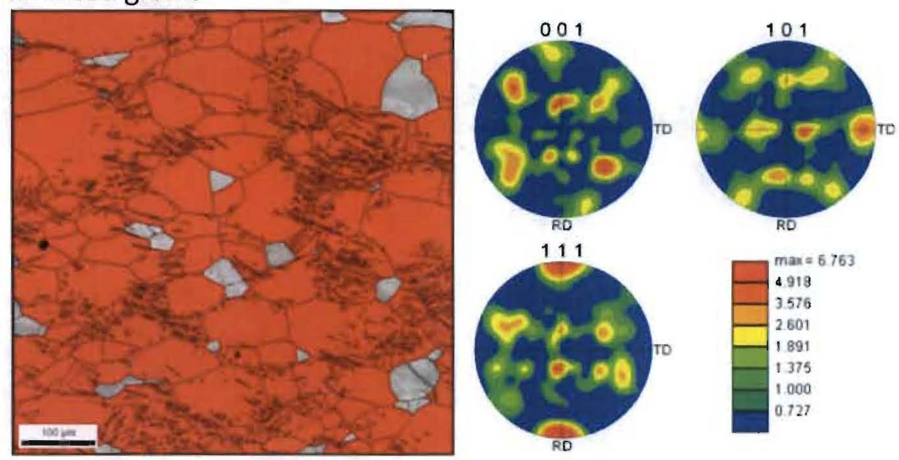
Twinned vs. Non-Twinned Grains

8mm in diameter and 4 mm thick, 2mm PETN pellet
(similar results in lower HE-drive specimen)

Non-twinned grains



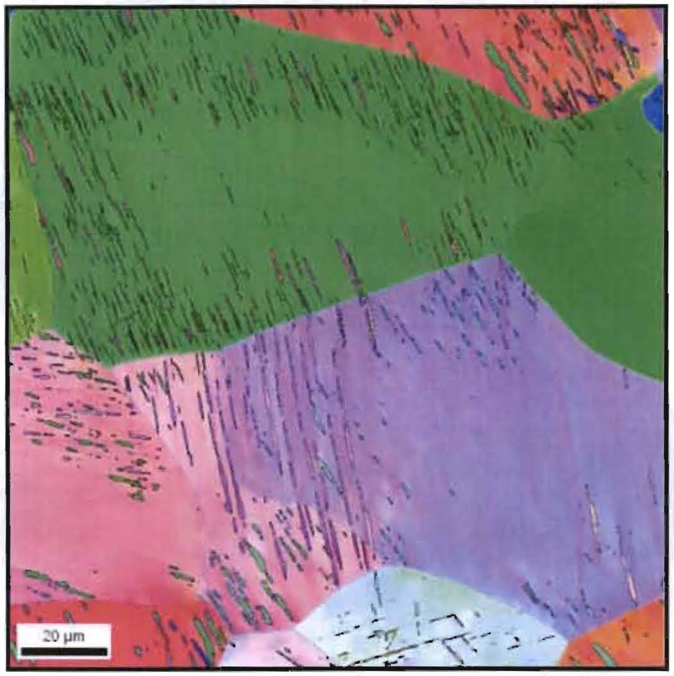
Twinned grains

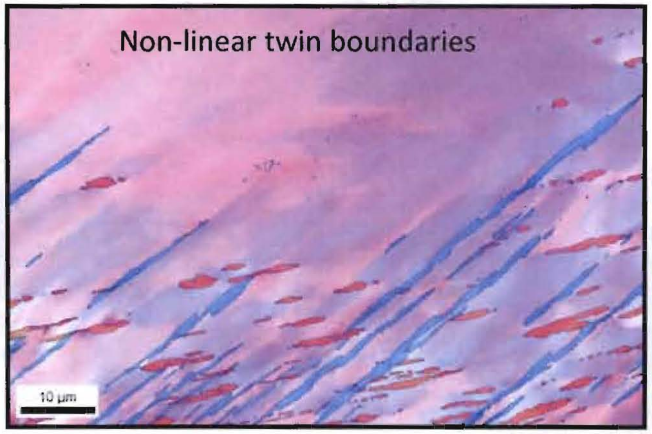


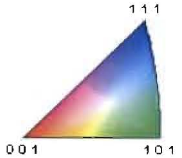
- No bulk texture differences found between non-twinned grains and twinned grains.
- A grain size effect was found indicating that grains below 25 microns did not twin.

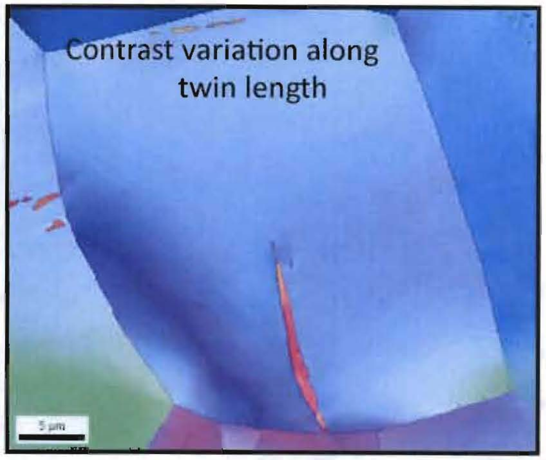
Morphology of Twins in HE-Driven Tantalum

- Twins form preferentially along the grain boundaries.
- More than one twin variant present in one grain.
- Many twins boundaries are no longer a straight line.
- Variable orientation/contrast along the length of some twins







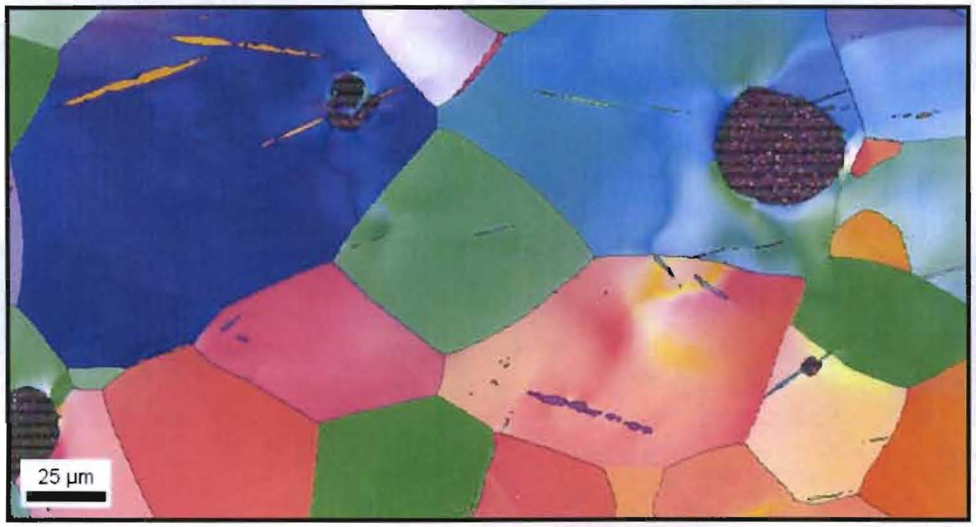


- Twins form at boundaries to mitigate compatibility stresses between adjacent grains.
- Based on their morphology, twins are formed during shock rise, then subjected to deformation during subsequent stages of shock evolution.

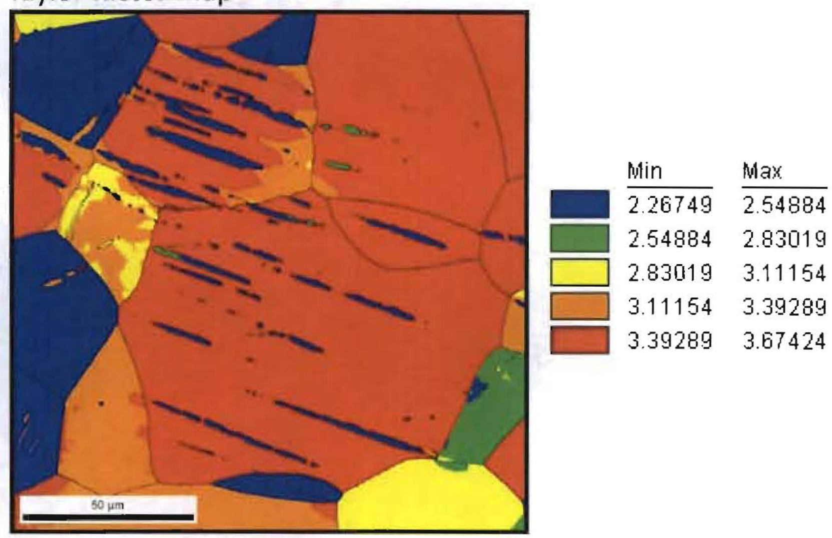
Damage Models Need to Account for Twinning

- Twin boundaries are preferred void nucleation sites in HE-driven tantalum.
- An average of 70% of the small voids analyzed were nucleated at twin boundaries.
- Taylor factor map indicates sharp differences at most twin boundaries.

Void damage nucleated at twin boundaries

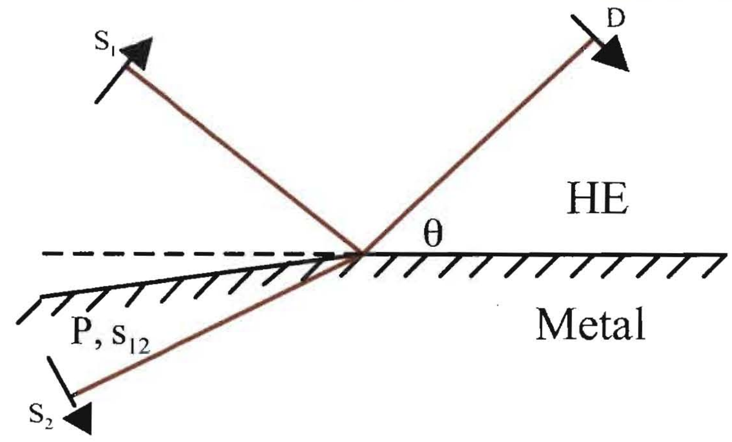


Taylor factor map



One cannot accurately model shock damage without understanding the twin nucleation process and including the effect of twinning on the deformation and damage evolution.

Modeling of Oblique Shock Loading of Ta

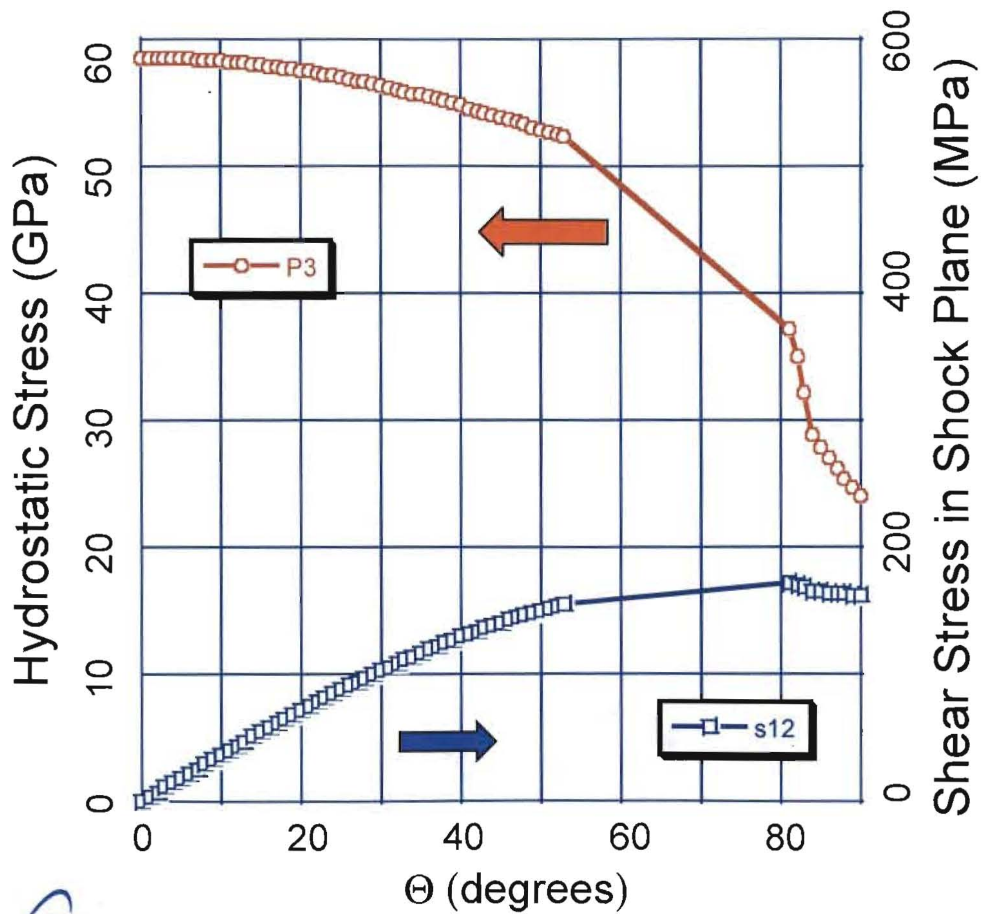


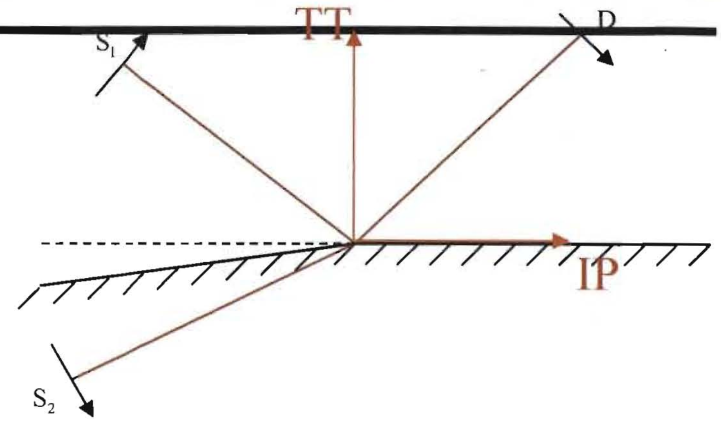
- Consider the interaction of an oblique detonation wave (D) with a PETN/metal interface as depicted by the right-going regular-reflection wave structure.

- The wave D propagates into non-reacted HE at an angle of obliquity defined by θ , with D reflecting from the interface as a gas shock into HE combustion products and transmitting shock into the Ta metal.

- Application of three-dimensional (3D) Jump Relationships to each of the three waves produces a nonlinear set of coupled, algebraic equations (11 equations containing 12 unknowns for each wave) involving conservation principles of mass, momentum, energy, Equation-of-State (EOS) and deviatoric constitutive information.

Tantalum – Spherical & Deviatoric Stress

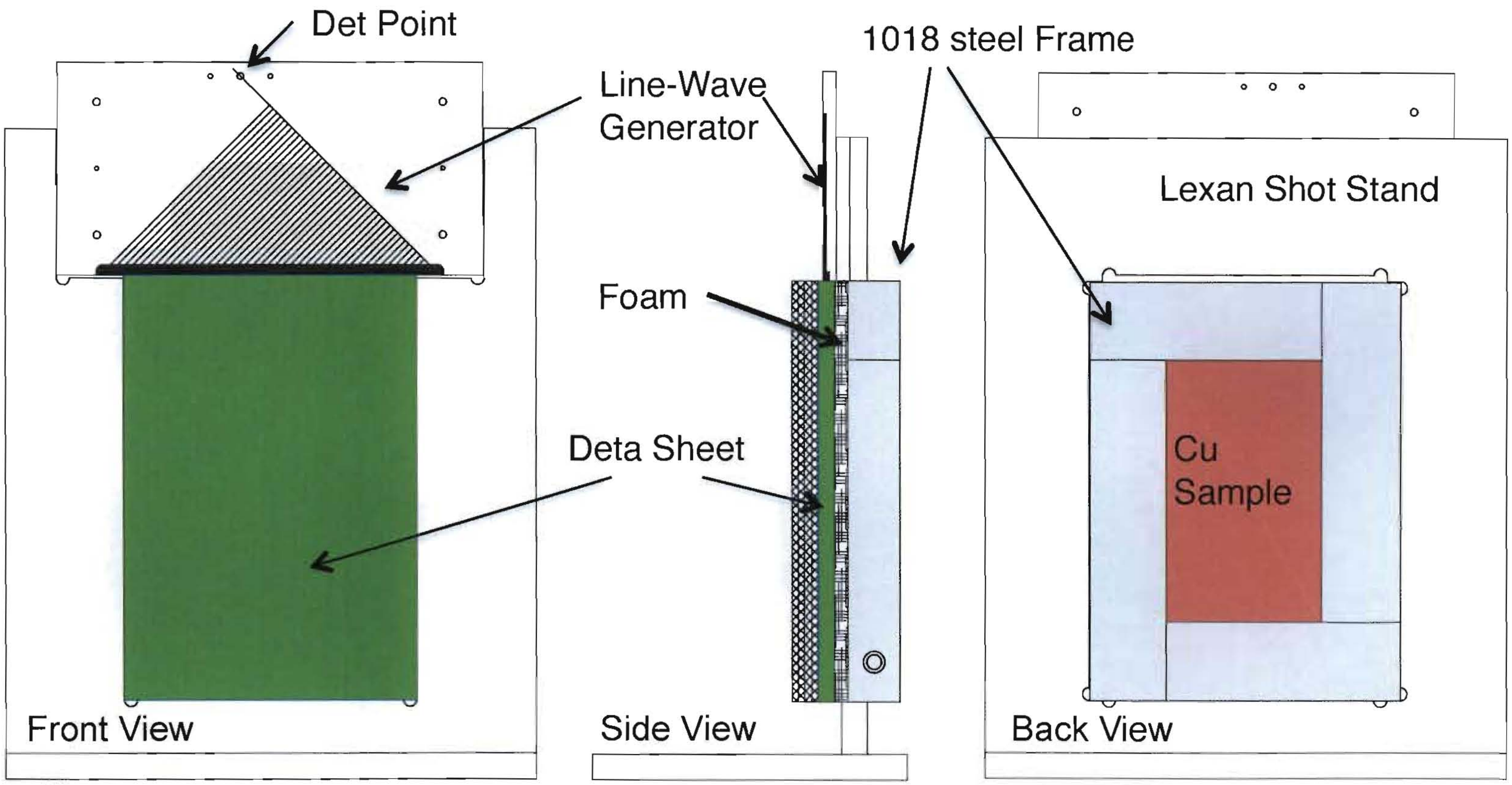




Two sources of shear possible:

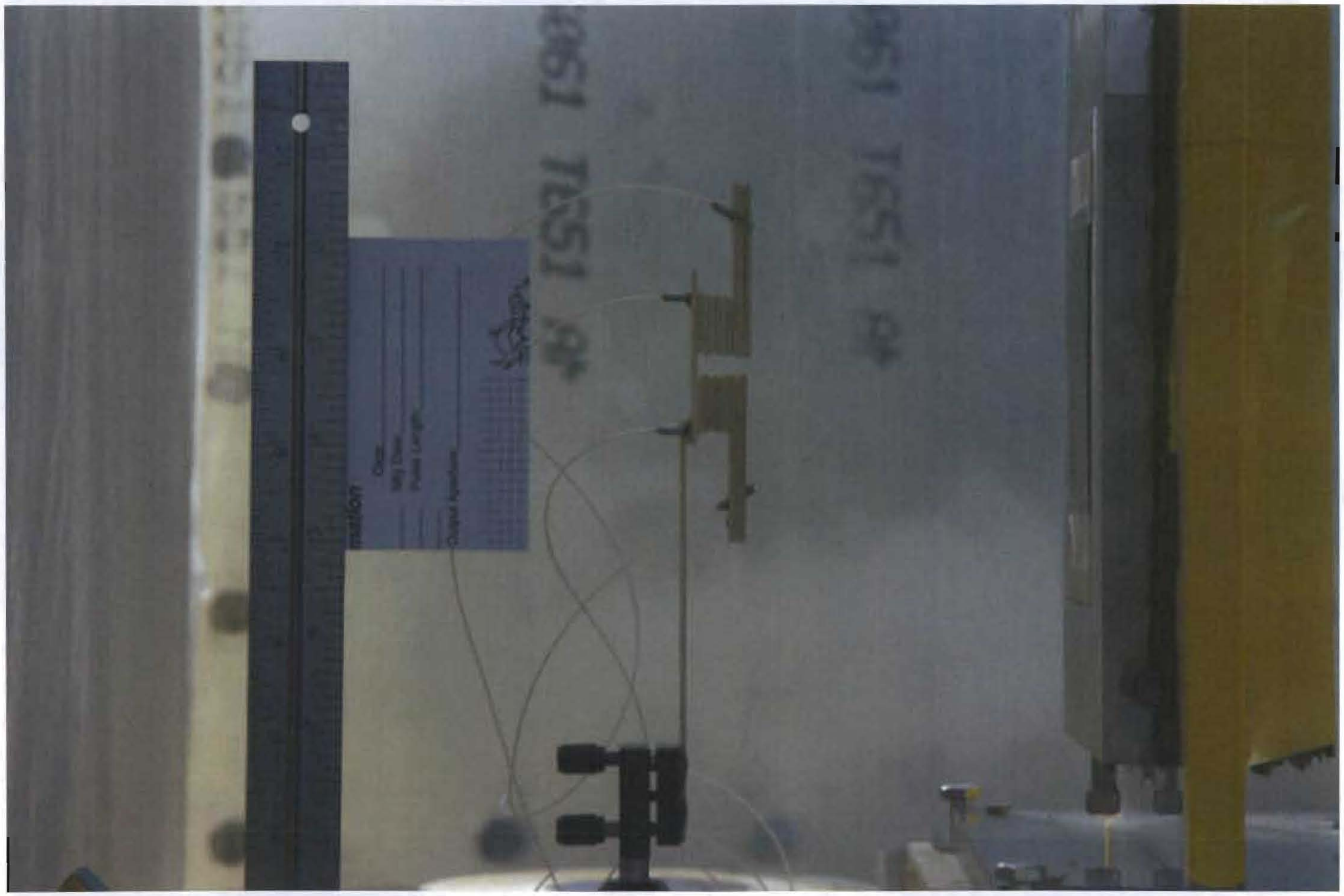
1) Change of ref frame from Shock to Lab
2) Induced shear from material anisotropies

Sweeping Detonation Drive: 8 mm Detasheet + .25" Foam



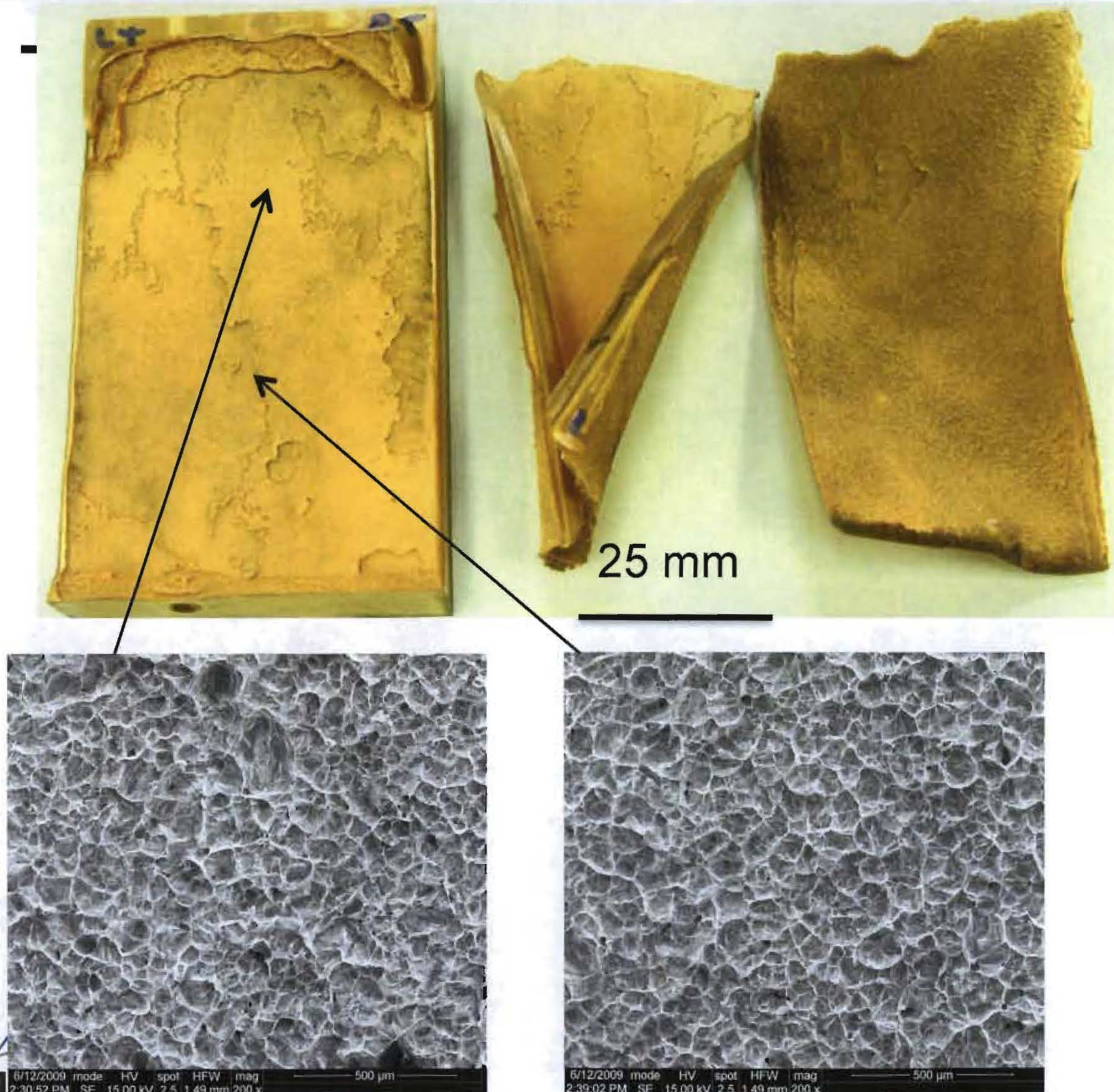
Sweeping Detonation-Wave Experimental Set-Up

Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam



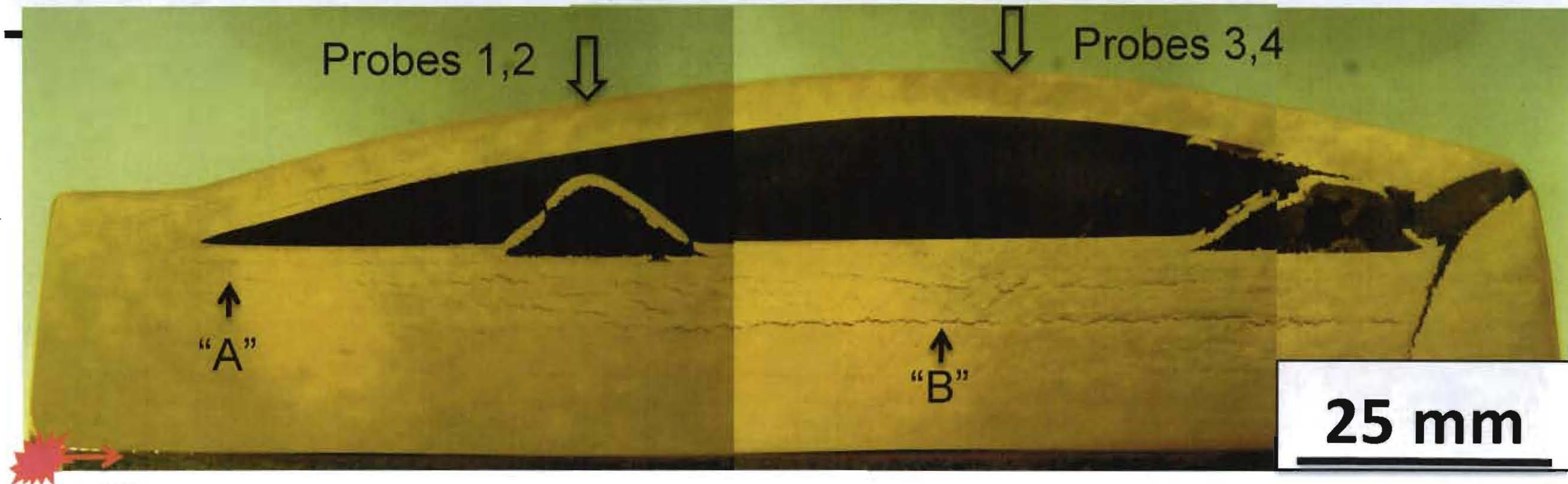
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

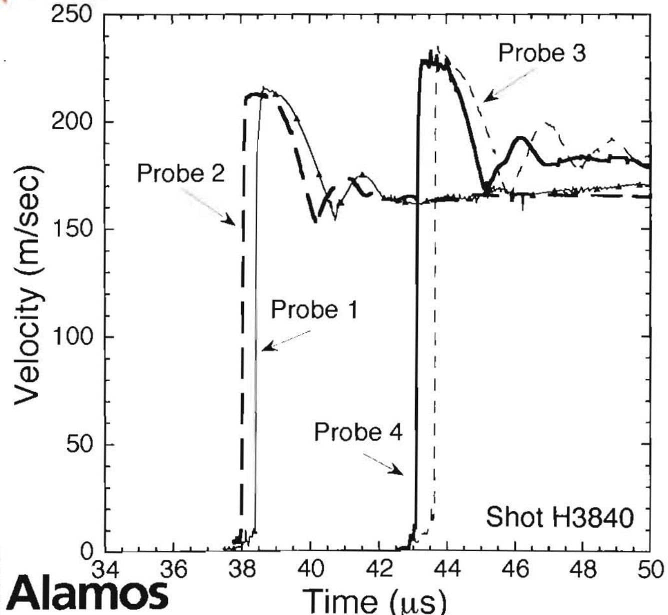
Sweeping Detonation Drive: 4 mm Detasheet in direct contact

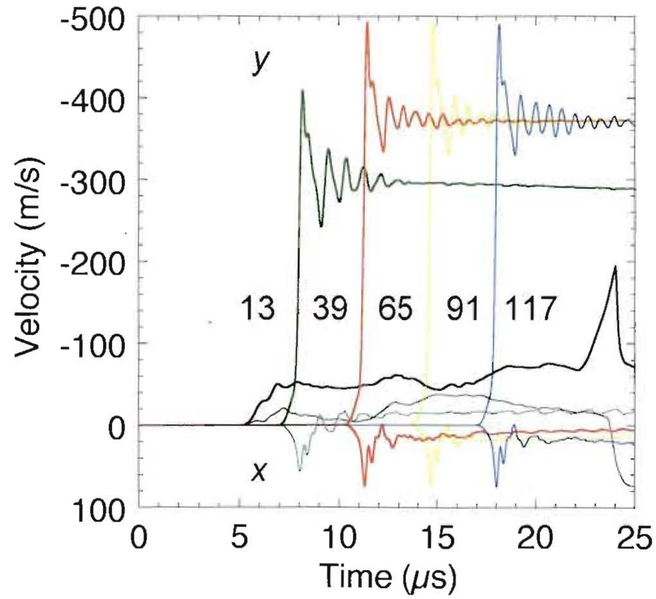


- The damage evolution is seen to consist of equiaxed ductile dimples consistent with a Mode I overload fracture process
- No evidence of shearing in the dimples was observed

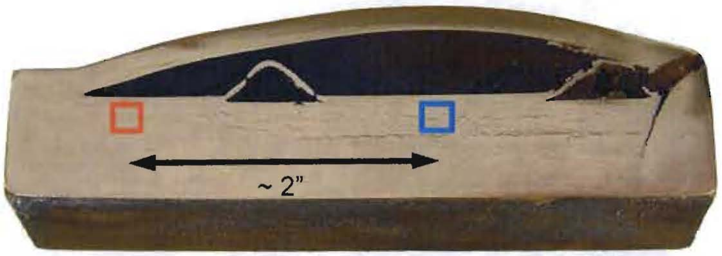
Sweeping Detonation Drive: 8 mm Detasheet + 6.35mm Foam

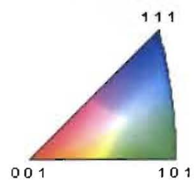


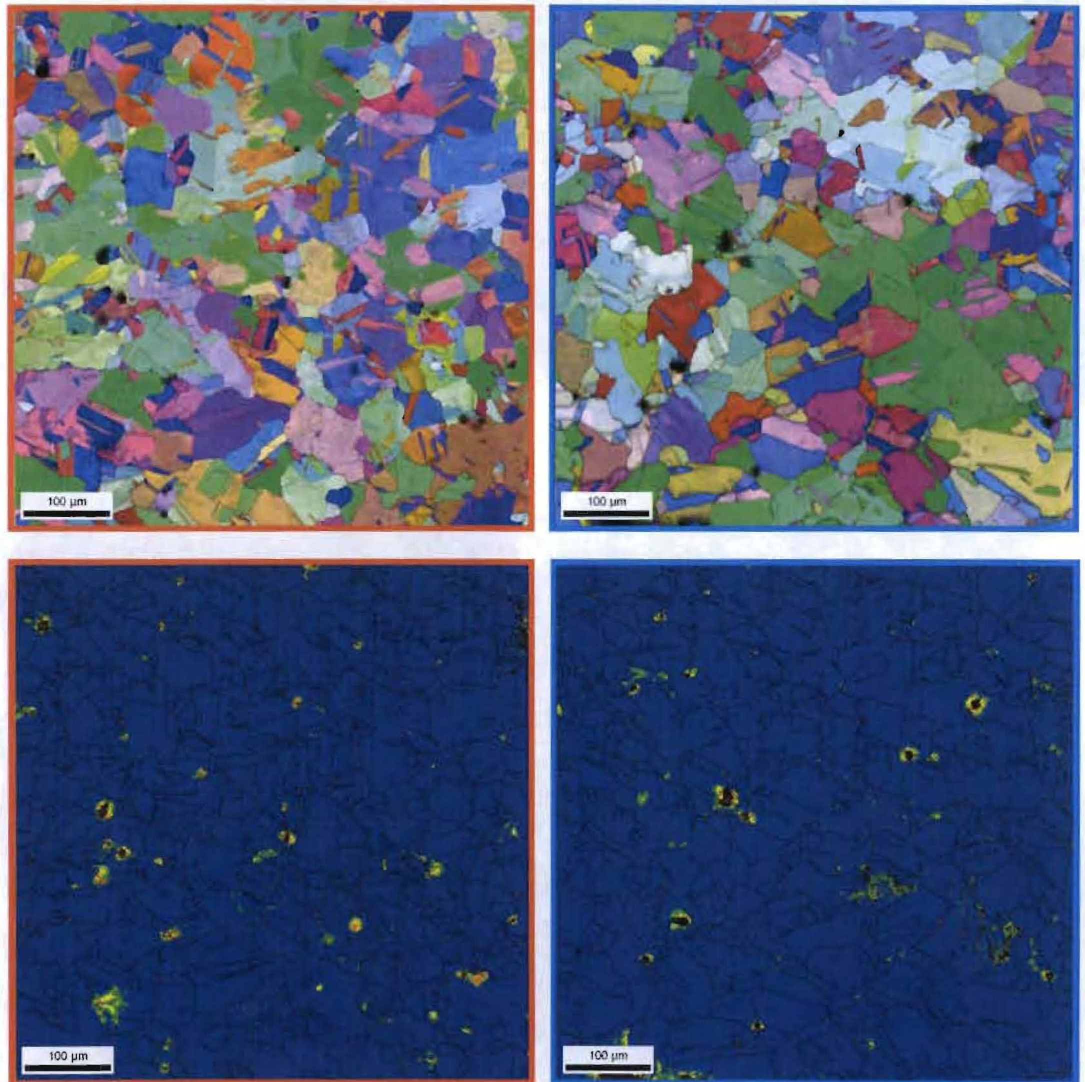




Total Macroscopic Damage Differs as Function of Shock Obliquity in Cu; the Plastic Processes that Evolve the Damage Remain Constant



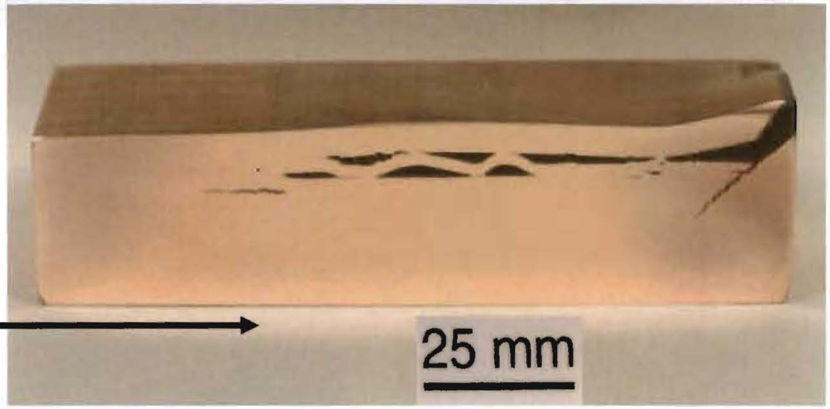


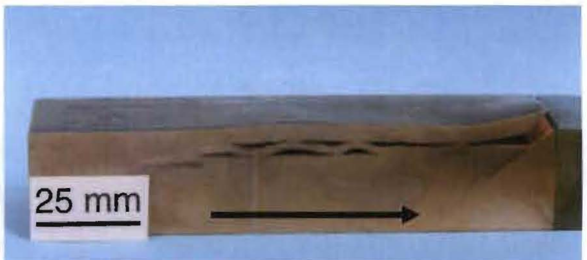


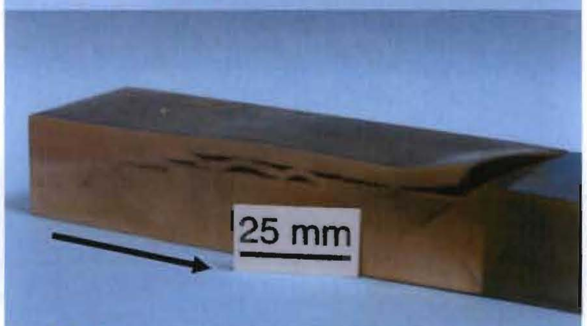
- No obvious shock obliquity effects
- No deformation twins detected
- Kernel average misorientation maps are similar

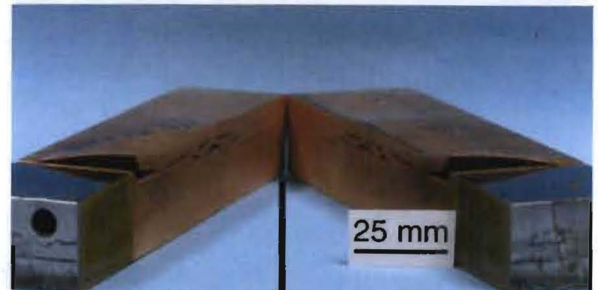
	Min	Max
Blue	0	2
Green	2	3
Yellow	3	4
Orange	4	5
Red	5	6

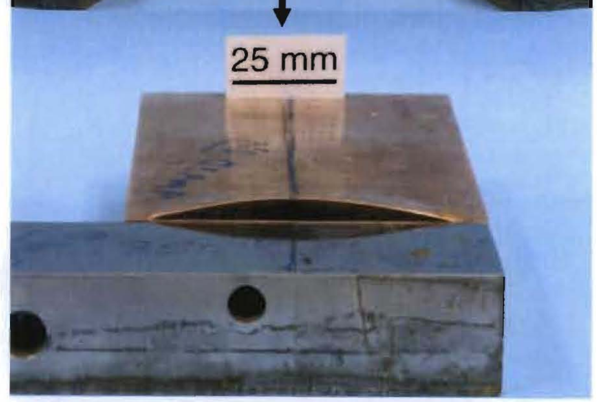
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

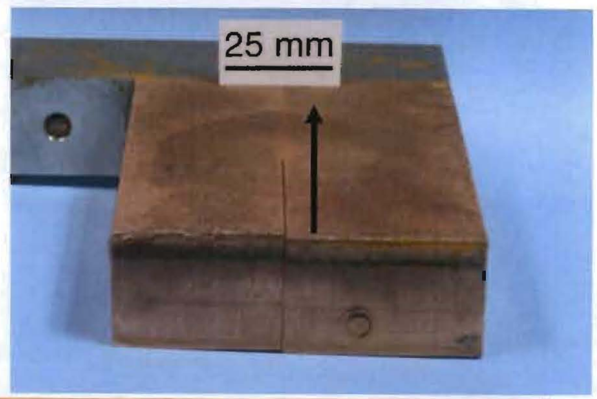




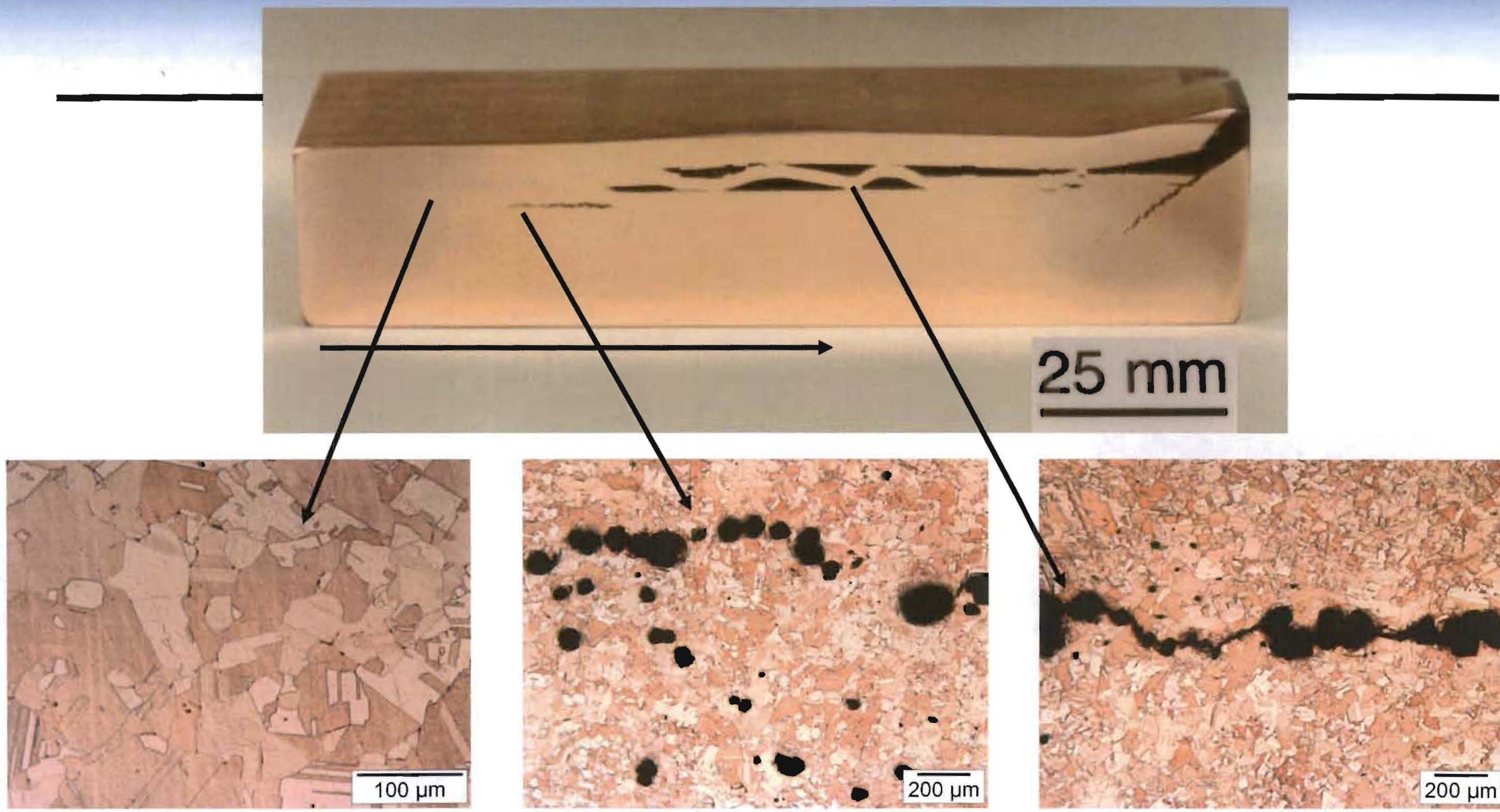




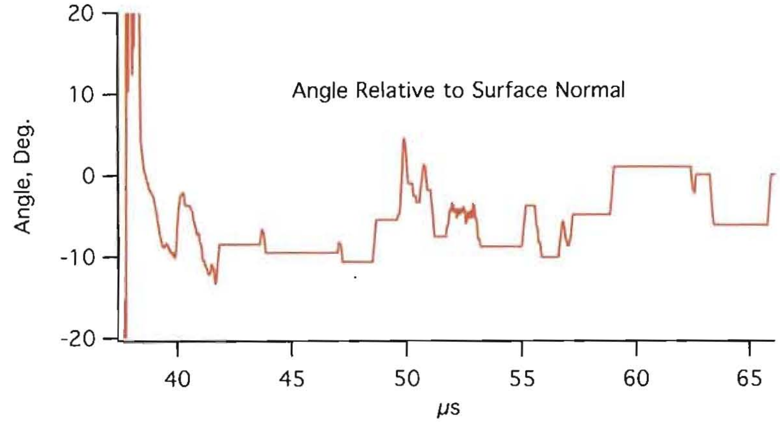


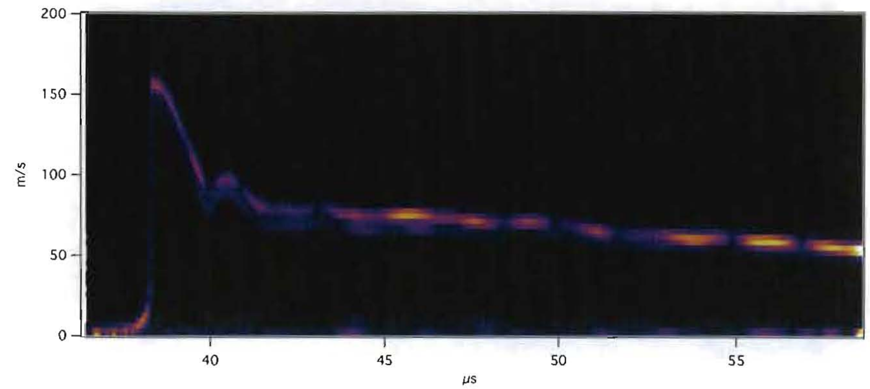


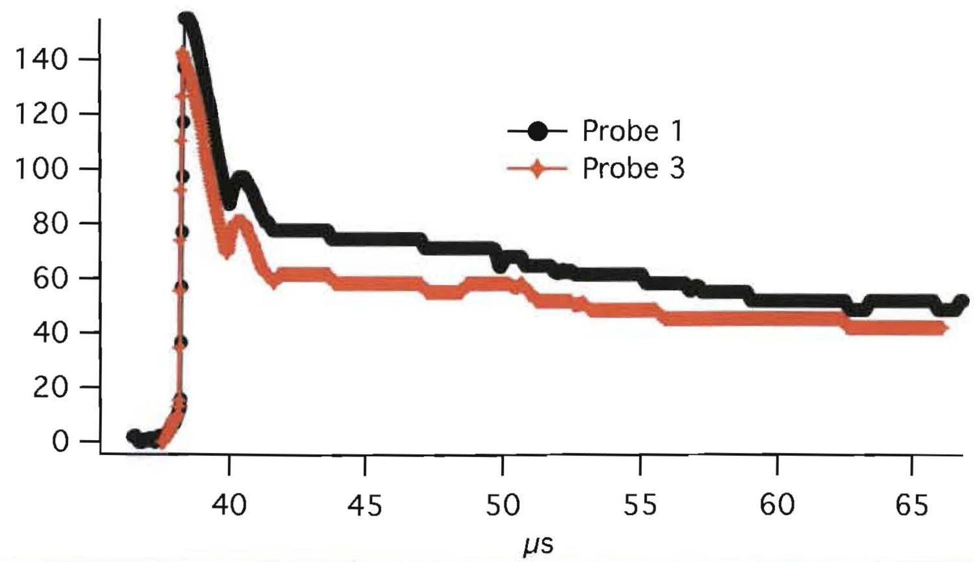
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam



PDV DATA - Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

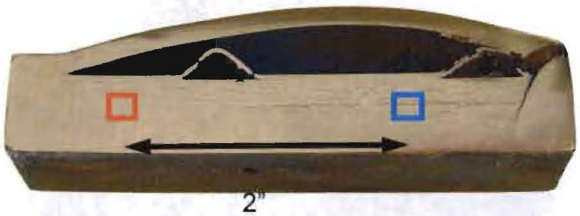




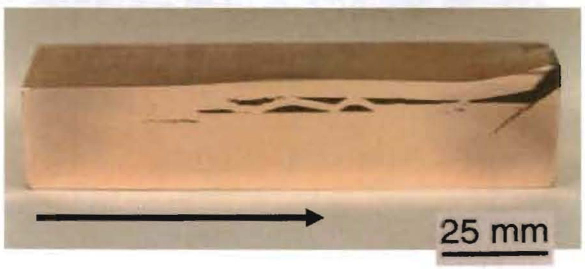


Cu – Sweeping-Wave Experiments

4mm detasheet direct on Cu



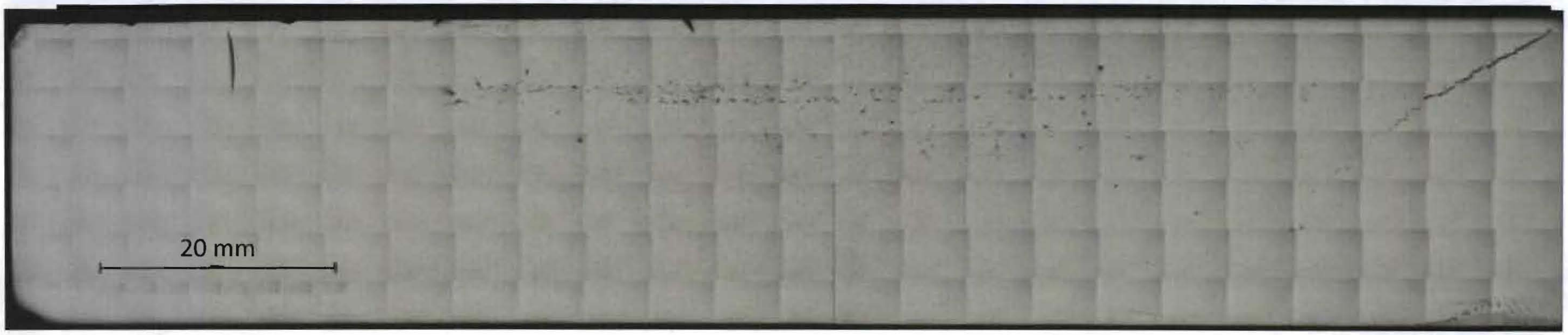
8mm detasheet + 7.62mm Foam



4mm detasheet + 7.62mm Foam

2mm detasheet + 7.62mm Foam

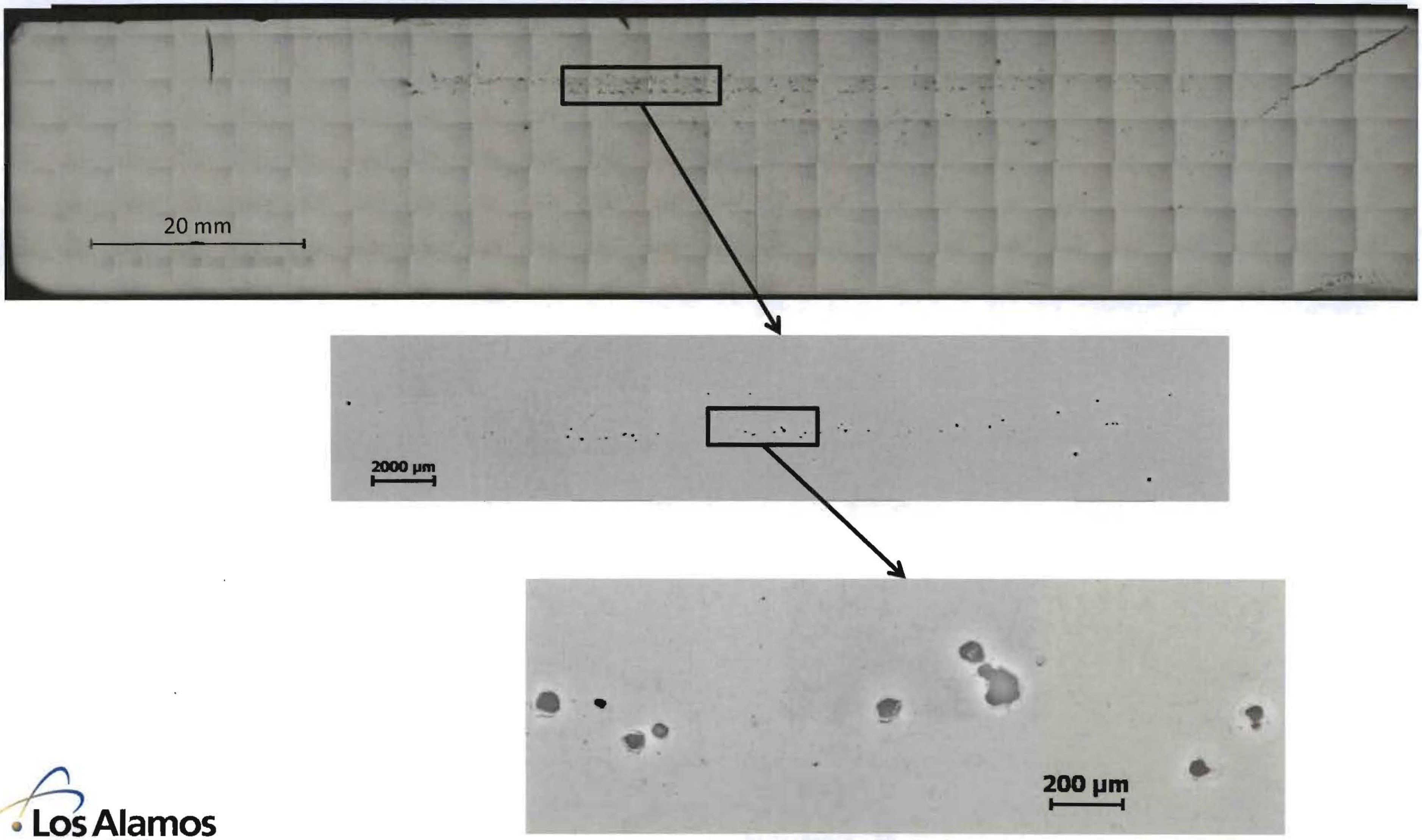
Cu -- 2mm detasheet + 7.62mm Foam



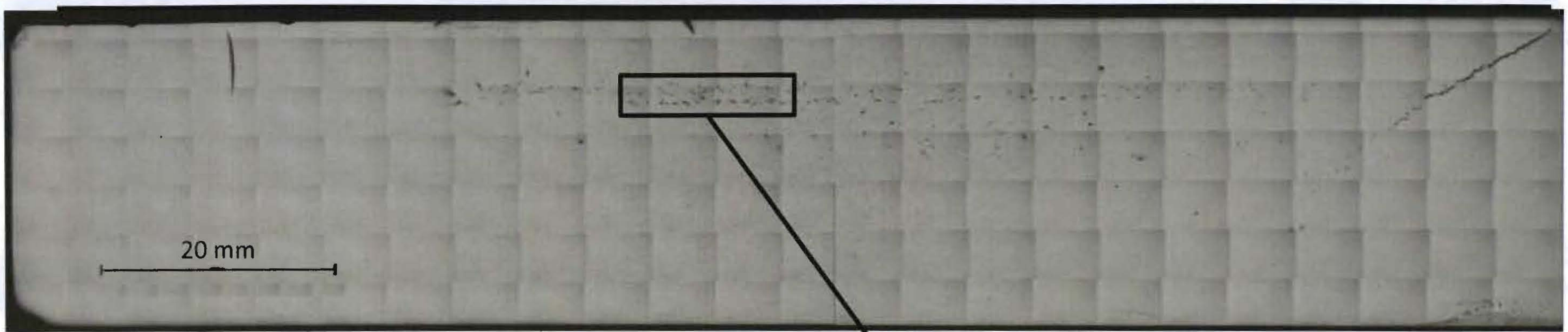
Reflected Light Image of Entire Surface

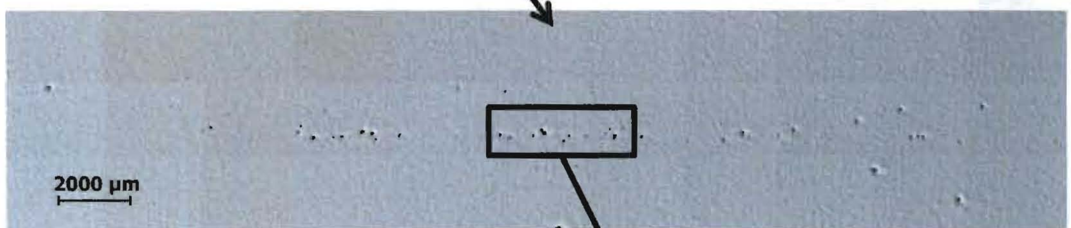
Cu -- 2mm detasheet + 7.62mm Foam

Reflected Light Image of Entire Surface with Details



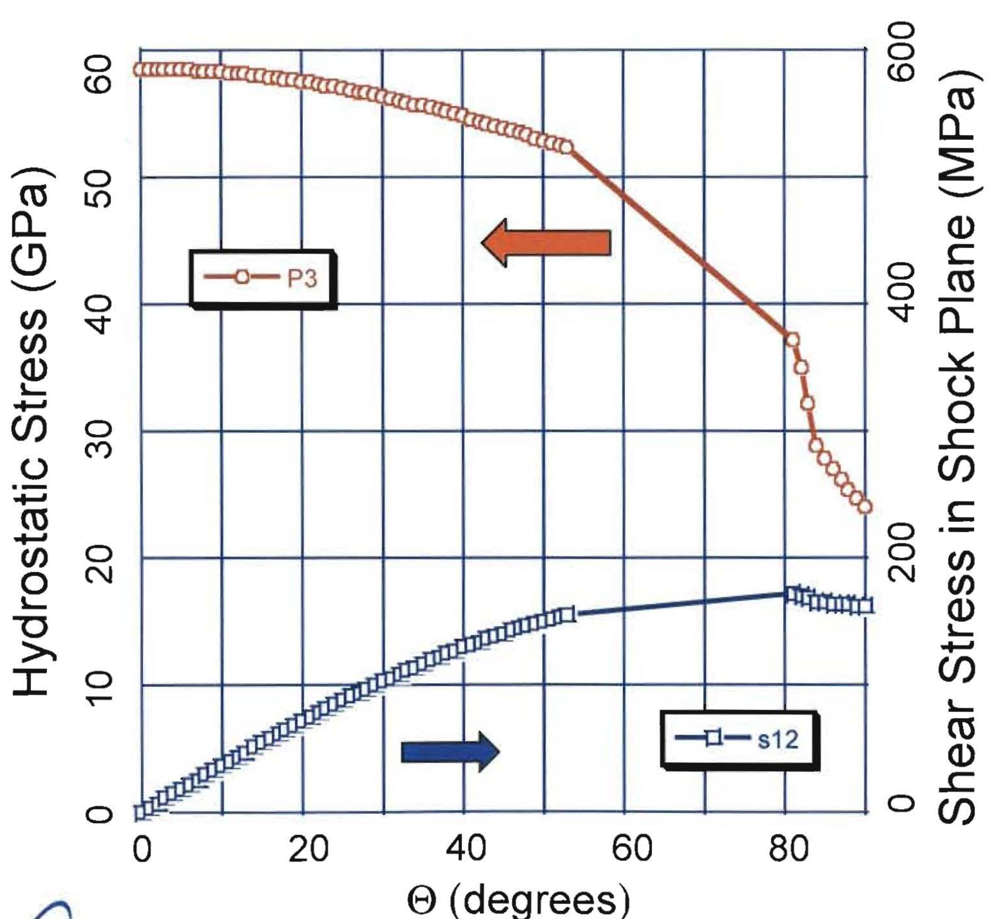
Cu -- 2mm detasheet + 7.62mm Foam

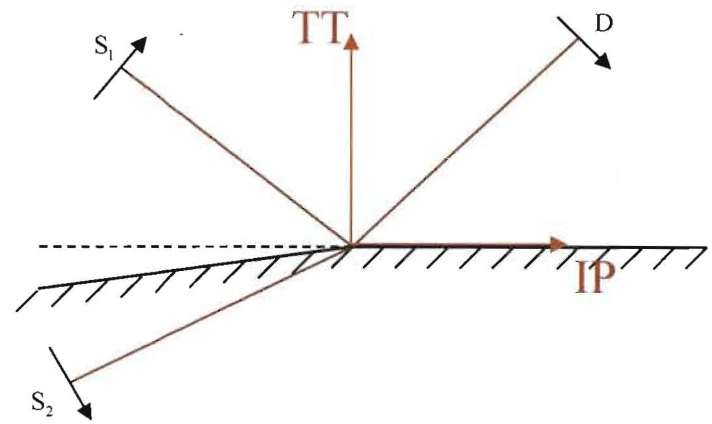




Reflected Light Image of Entire Surface with Interference Contrast Images of Details

Tantalum – Spherical & Deviatoric Stress



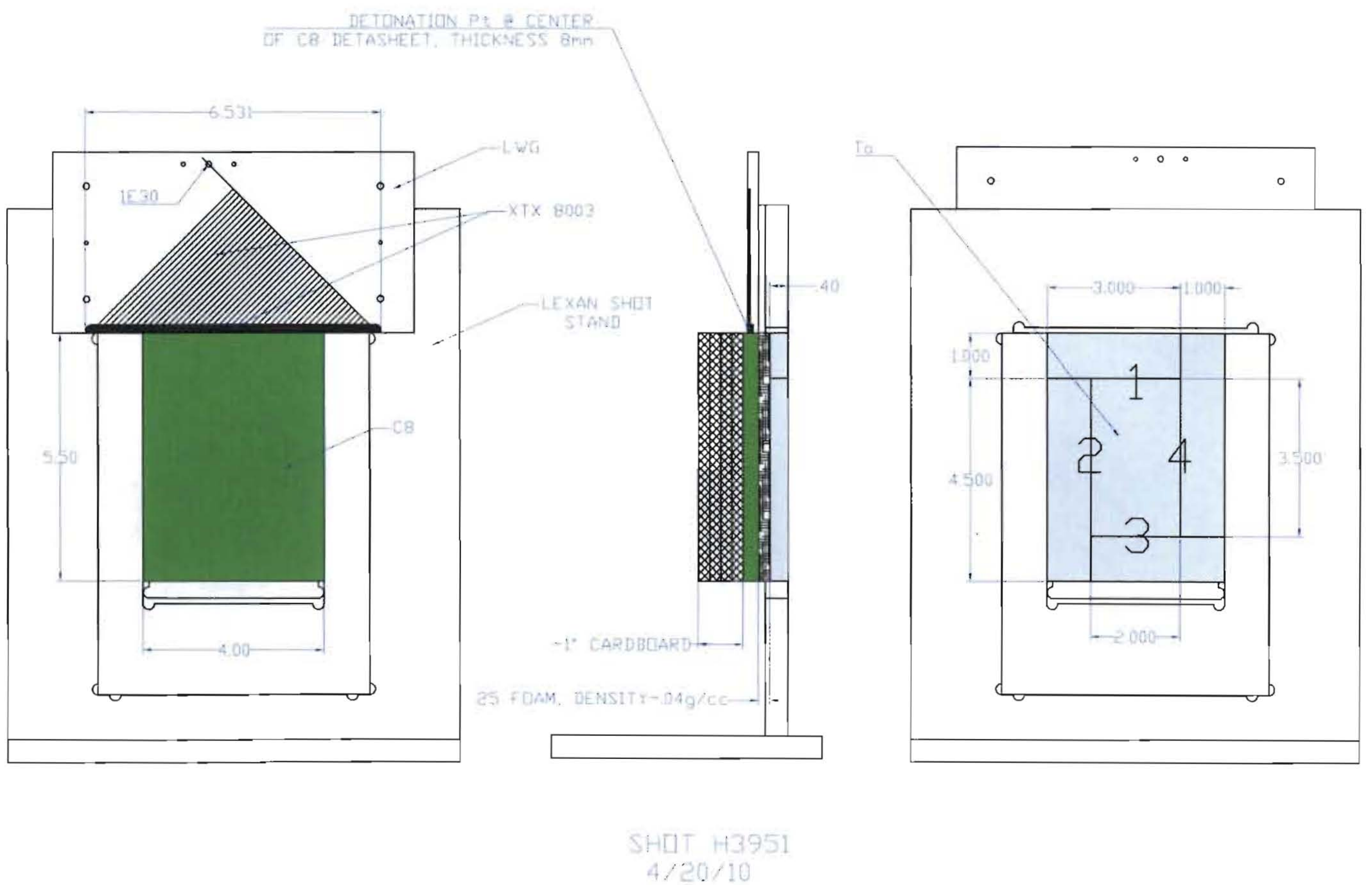


Two sources of shear possible:
1) Change of ref frame from Shock to Lab
2) Induced shear from material anisotropies

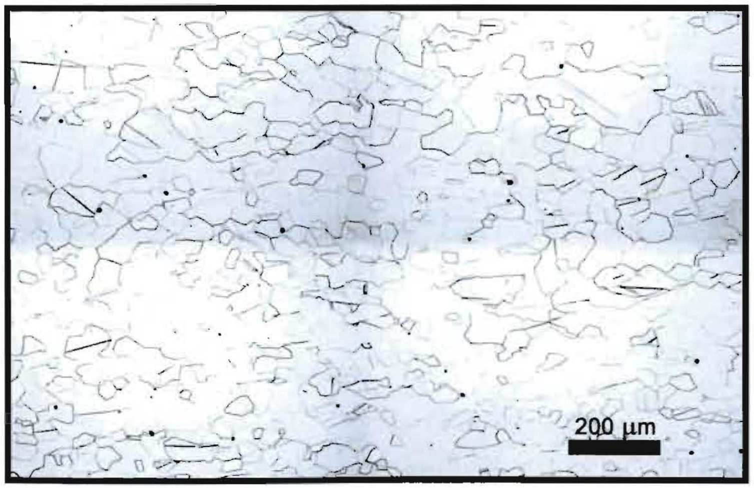
OBLIQUE SHOCK IN TANTALUM PLATE

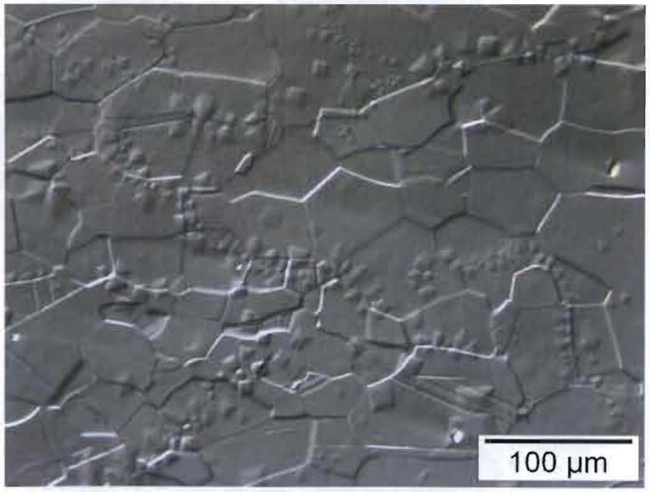
MST-8, Materials Science and Technology Division

1st Sweeping Spallation Experiment on Ta

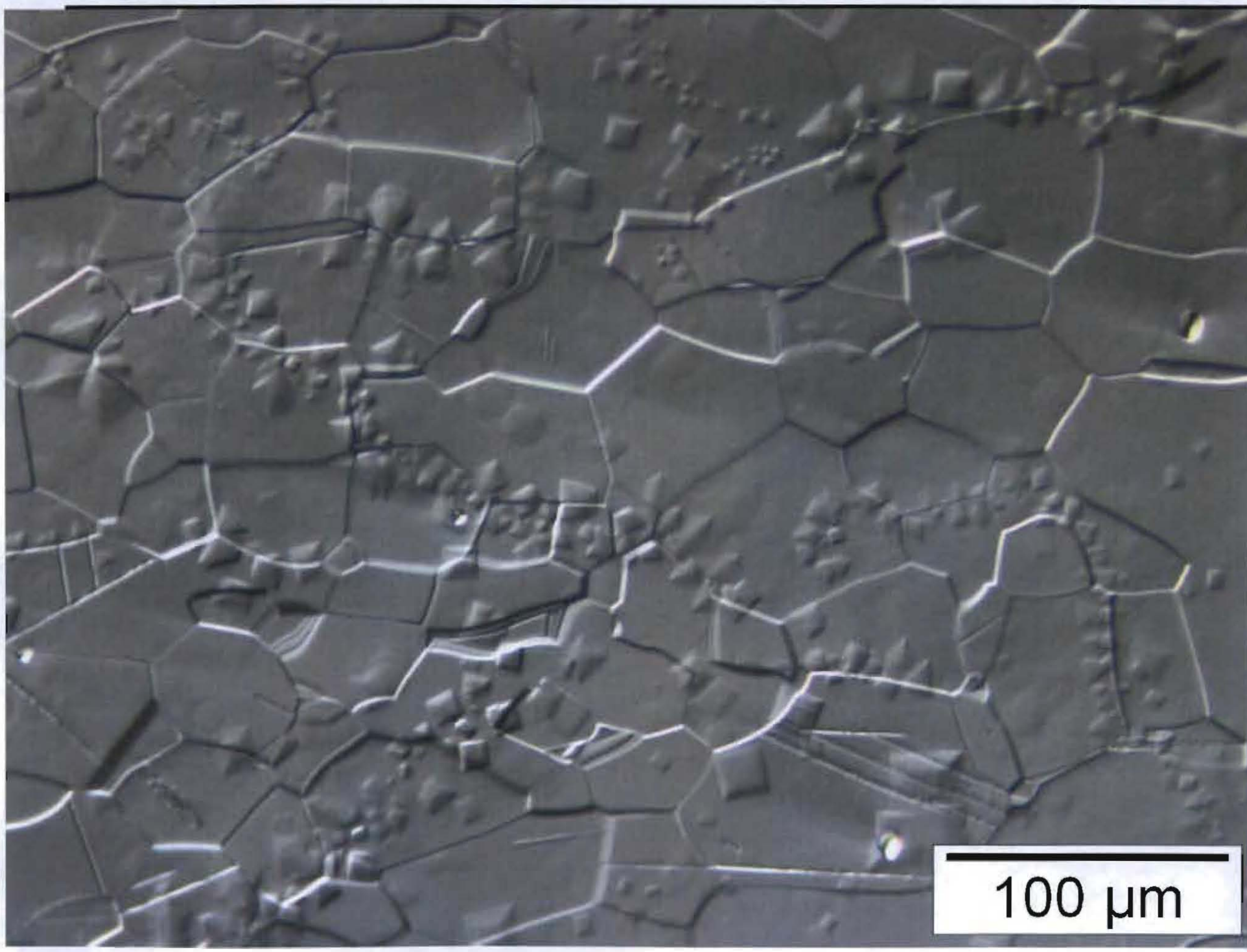


Similarly, Larger Scale Sweeping Detonation Experiments Are Being Conducted on Ta

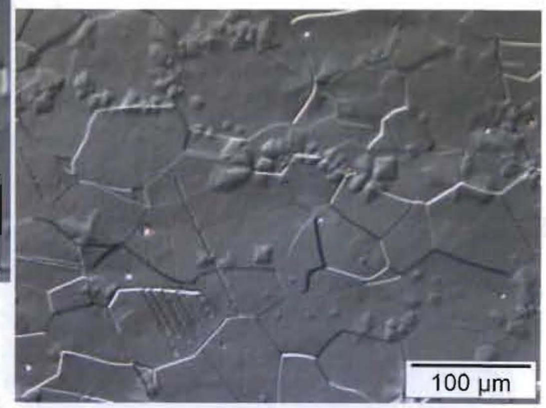




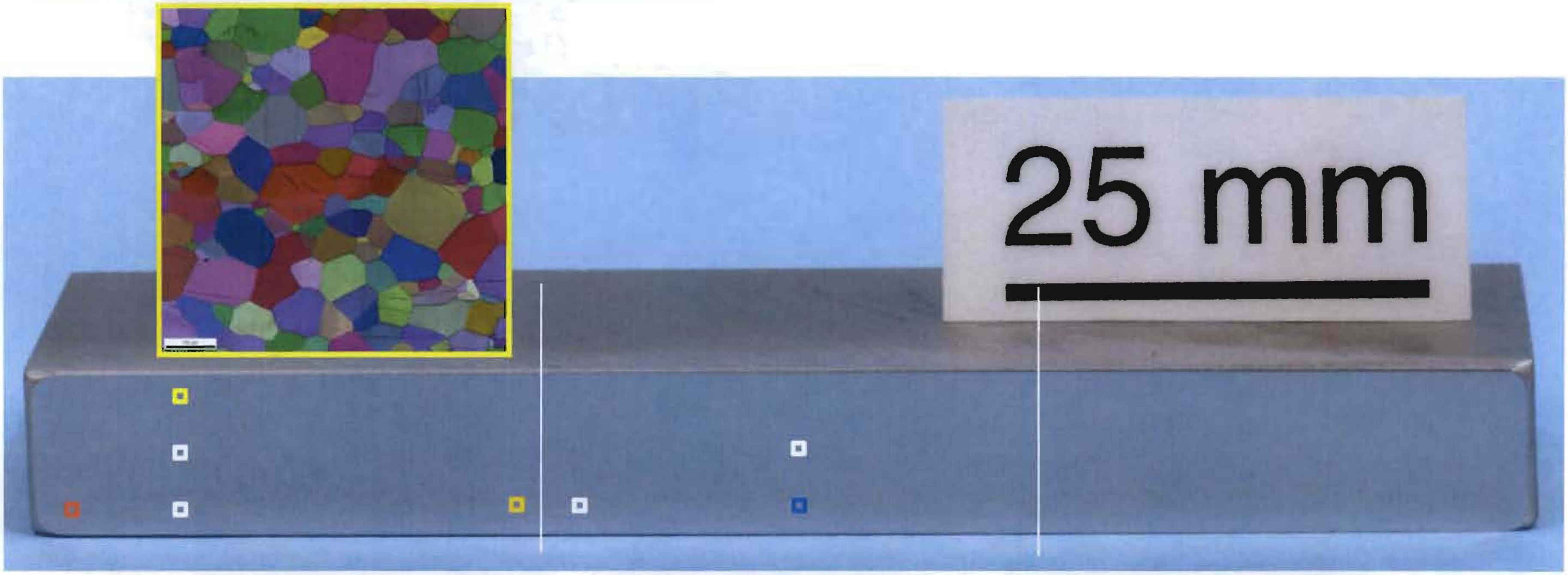
1st Sweeping Spallation Experiment on Ta

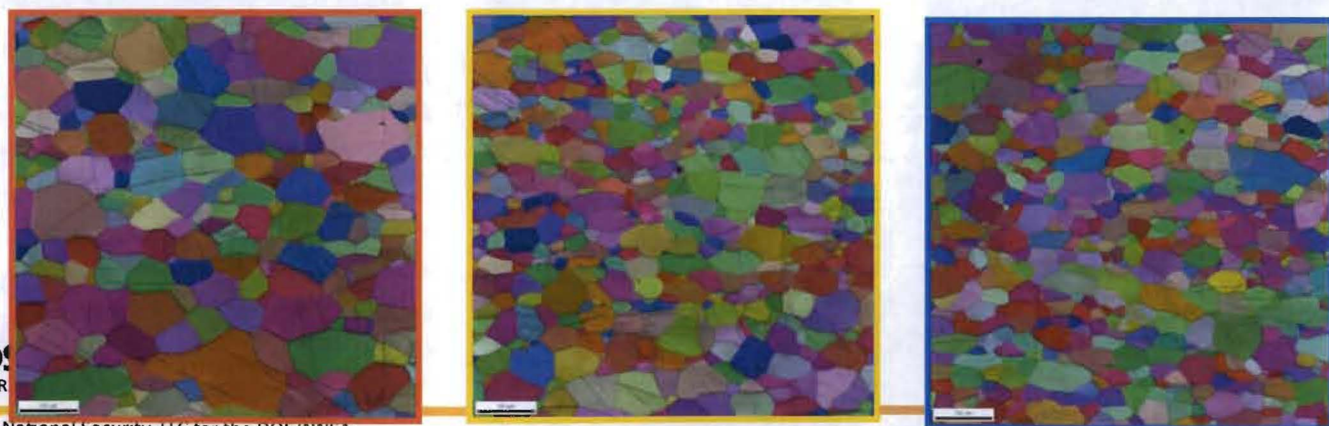


Optical metallography reveals slip-line surface offsets on the polished and etched plane section. Dislocation slip lines are seen concentrated along grain boundaries. Deformation twins are also seen.

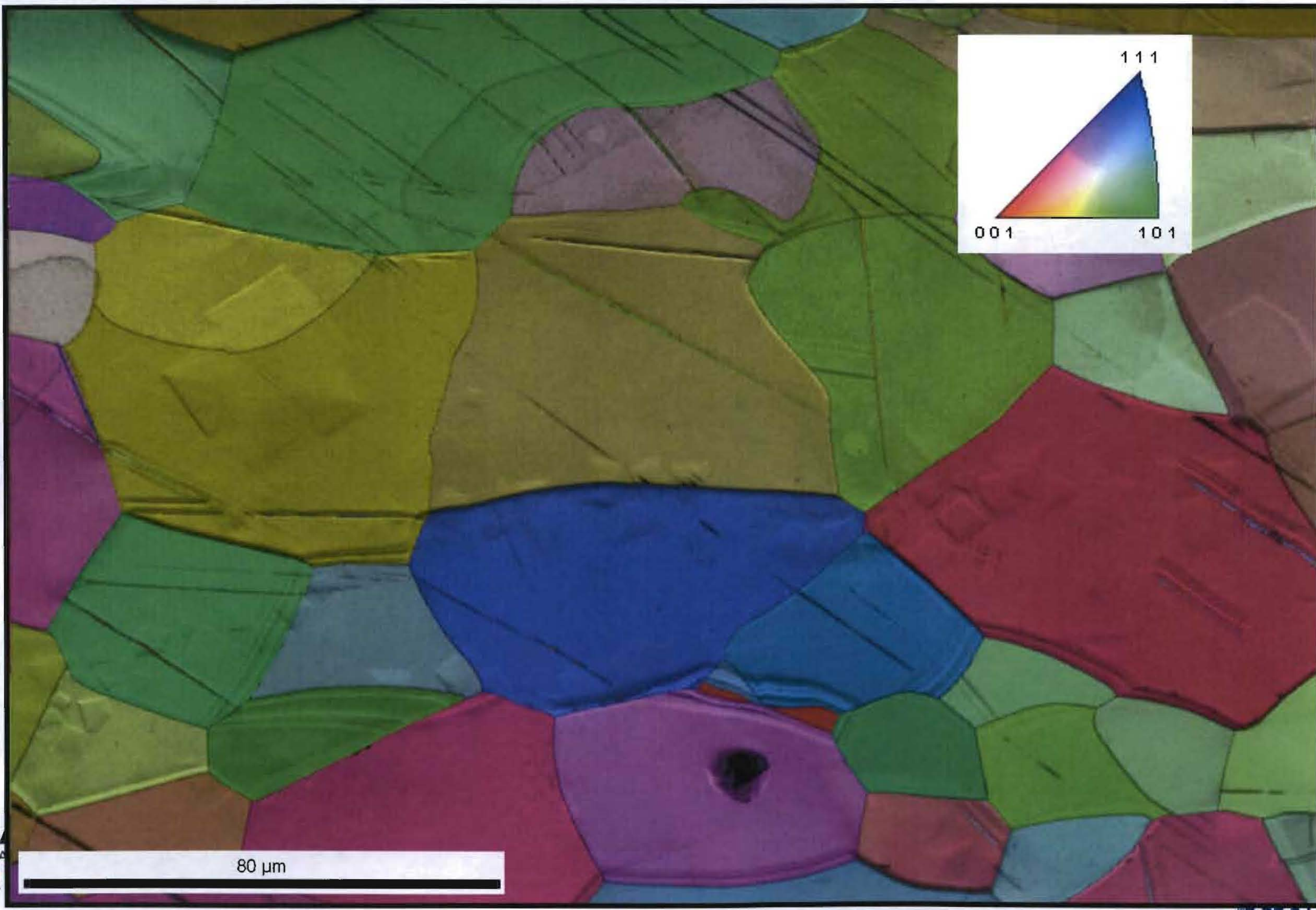


Initial Characterization Aimed at Linking Evolving Substructure to Damage Nucleation/Growth as Function of the Loading Profile



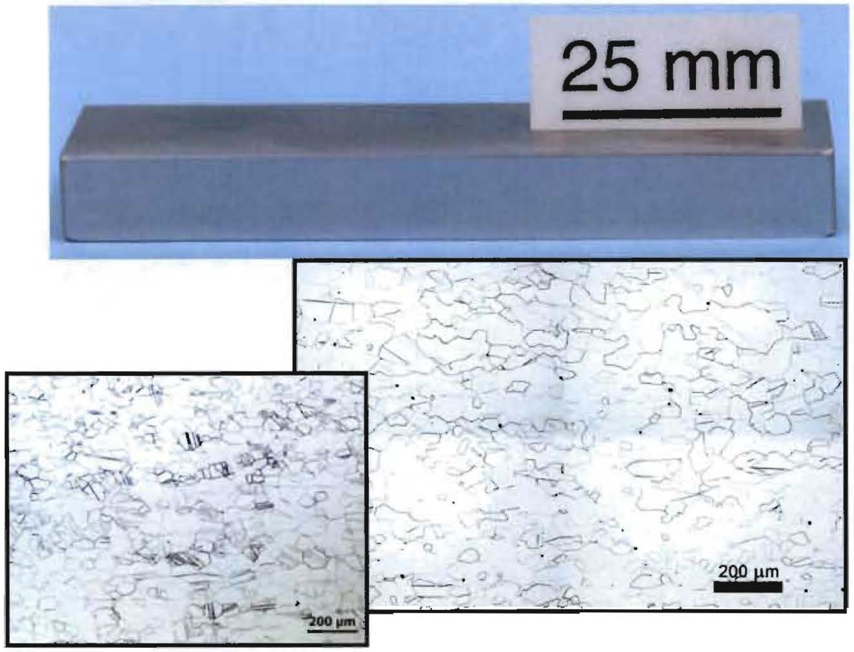


EBSD of dislocations - IPF map with IQ map superimposed



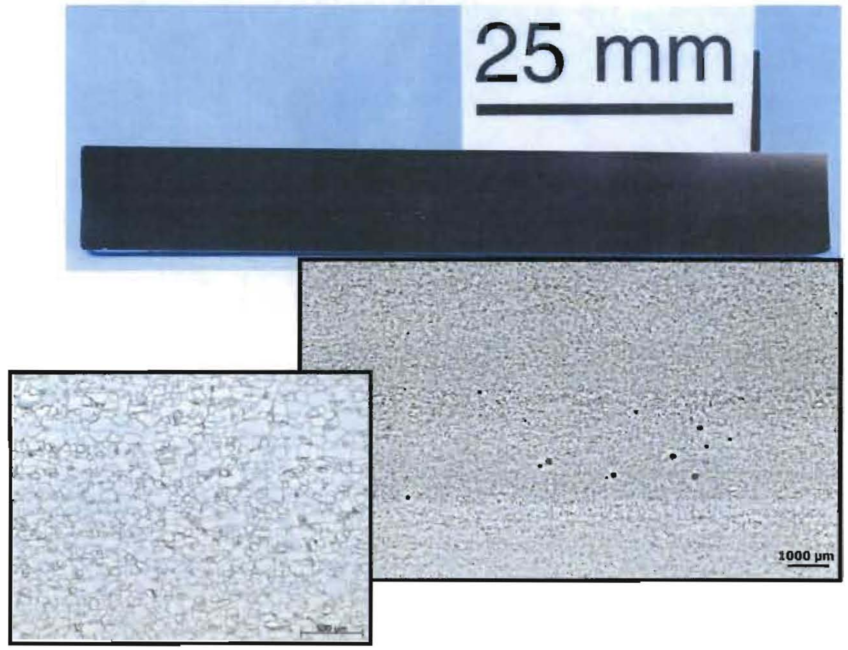
Optical Microscopy - Comparison

Shot 1 (3.5" long, 10mm thick, 8mm HE, 1/4" foam)



- Very incipient damage - no defined spall plane
- Small voids (up to 10µm diameter) scattered throughout the microstructure
- Heterogeneous twinning
- 65-70% of voids appear to be intragranular (some related to twin boundaries)

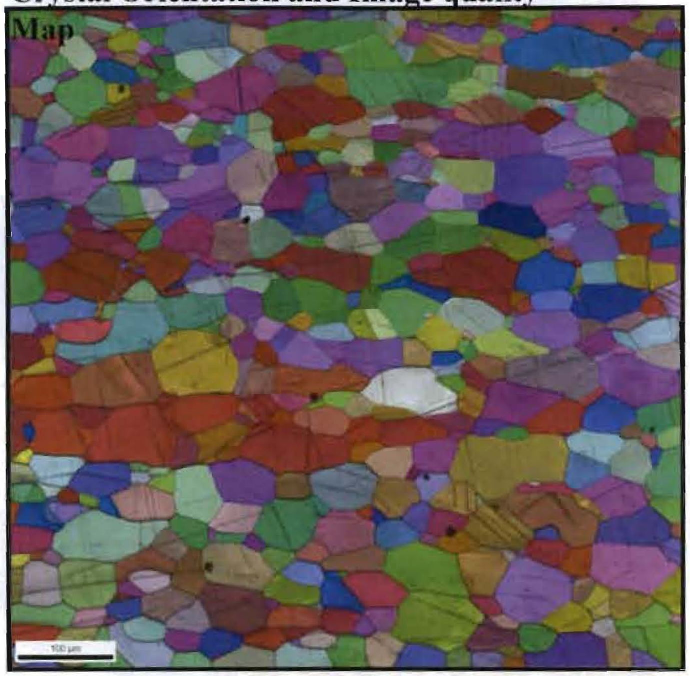
Shot 2 (3.5" long, 10mm thick, 8mm HE, 1/8" foam)

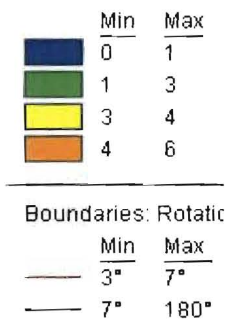


- More advanced damage state, vaguely defined spall plane
- Two stronger void damage zones
- Larger voids (up to 200µm diameter)
- Strong localization where voids are nucleated
- Heterogeneous twinning , possibly with higher density along the centerline

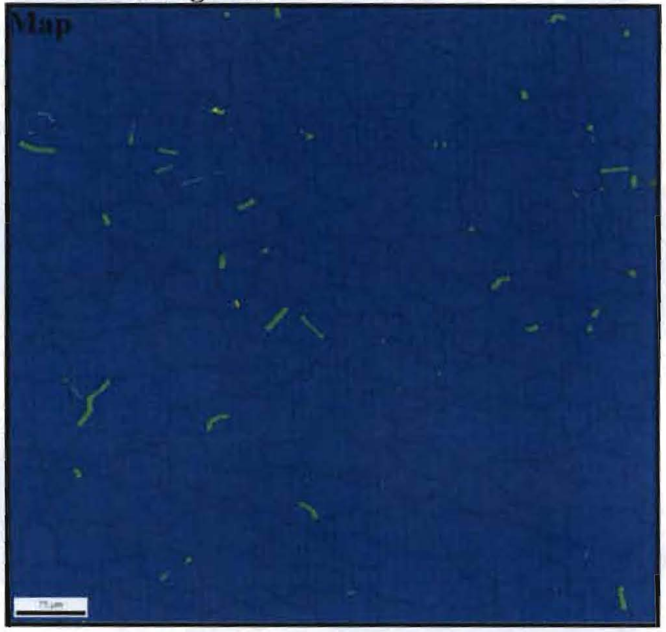
EBSD Analysis – Shot 1 (3.5" long, 10mm thick, 8mm HE, 1/4" foam)

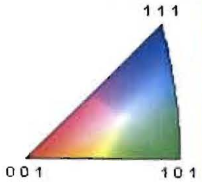
Crystal Orientation and Image quality Map





Kernel Average Misorientation Map

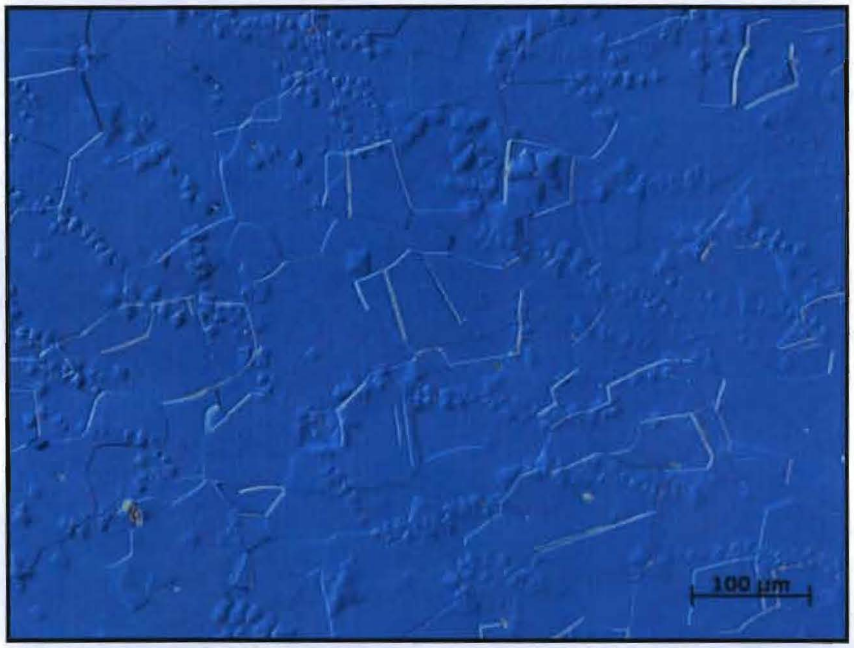




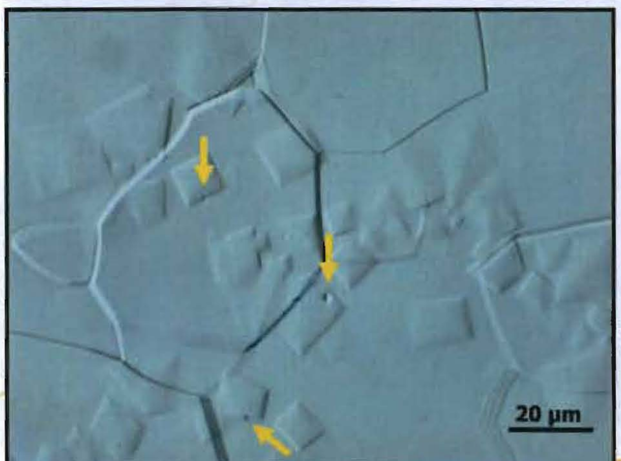
Electron Backscattered Diffraction analysis indicates:
- **No microstructural disturbance around voids**
- **No deformation affected material (aside from presence of twins)**
- **KAM map is similar to that of the undeformed material**

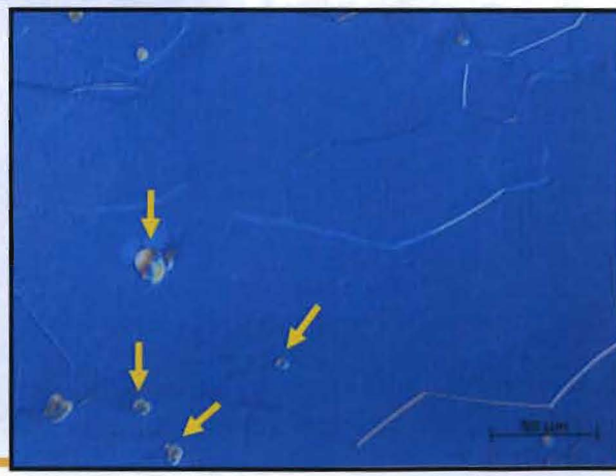
KAM map – as received material

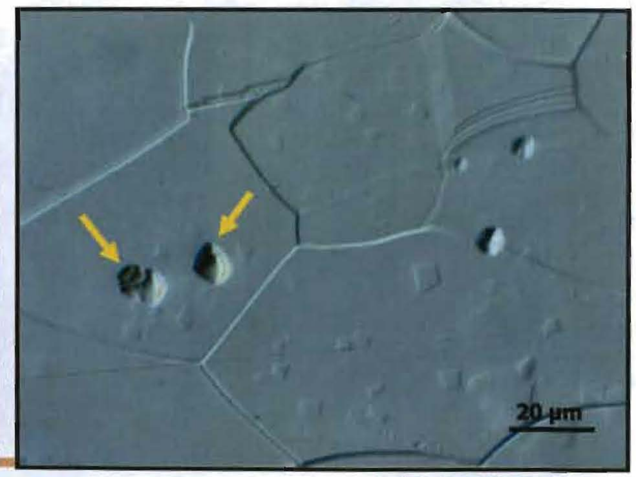
Void Nucleation Aspects– Shot 1 (3.5" long, 10mm thick, 8mm HE, 1/4" foam)



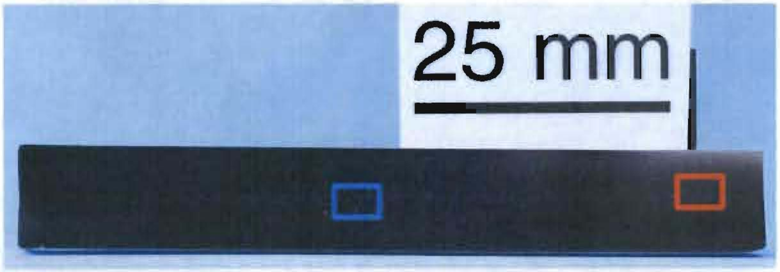
- **Dislocation etch patterns were revealed**
- **Intragranular voids that are not related to twin boundaries are spatially correlated to dislocations (see orange arrows below)**
- **The stress fields that result from the compressive and tensile forces around different dislocations interact with one another and lead to void nucleation?**

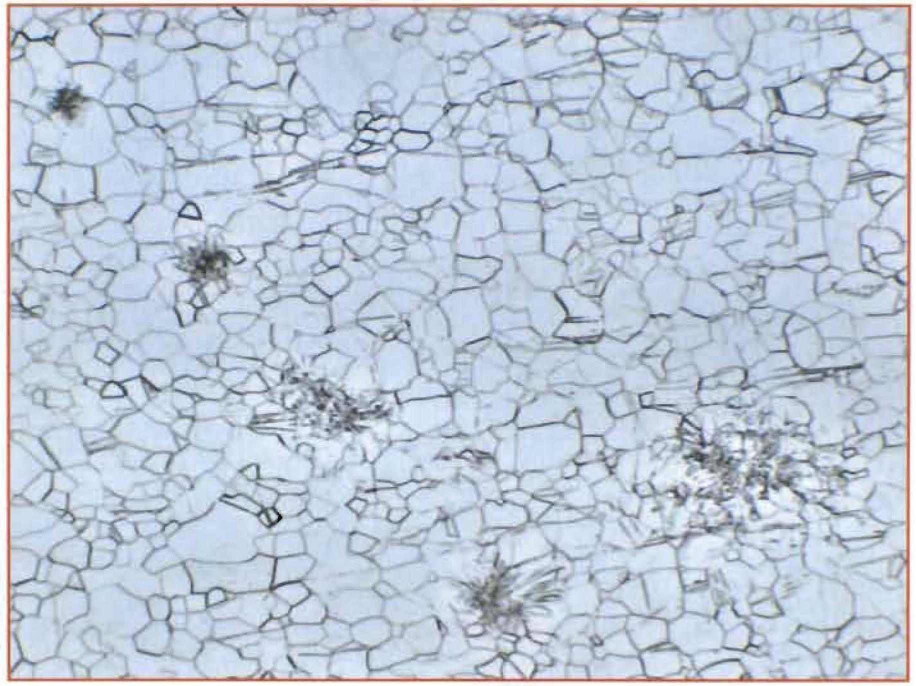


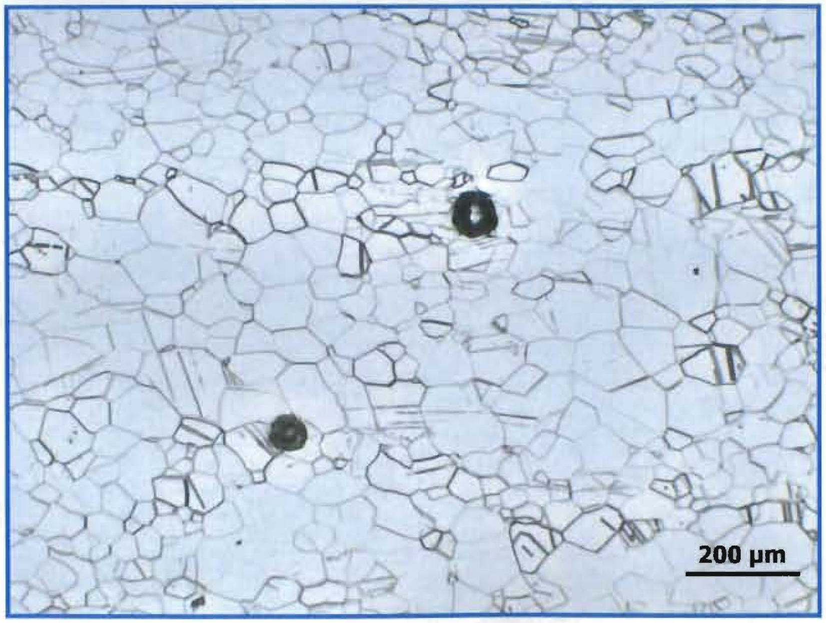


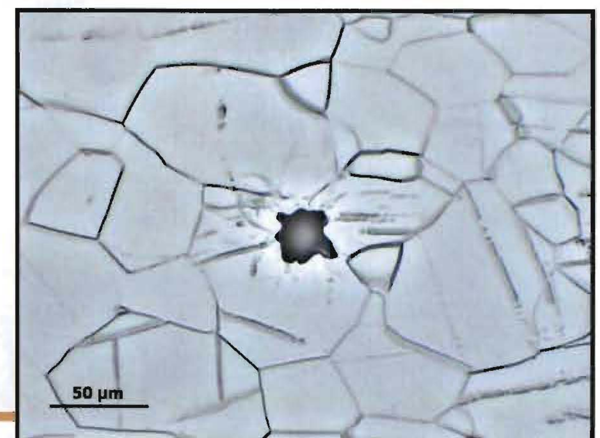


Optical Microscopy– Shot 2 (3.5" long, 10mm thick, 8mm HE, 1/8" foam)





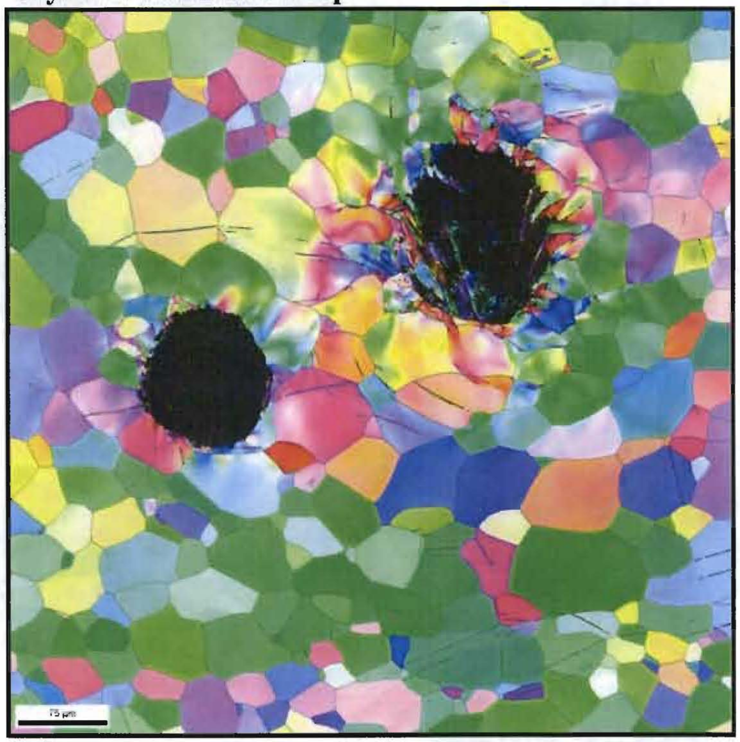


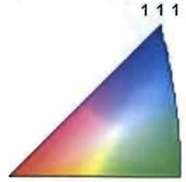


- While "fully-grown" voids appear round, incipient damage areas indicate that they are the result of multiple small voids that grow and coalesce.

EBSD Analysis– Shot 2 (3.5" long, 10mm thick, 8mm HE, 1/8" foam)

Crystal Orientation Map

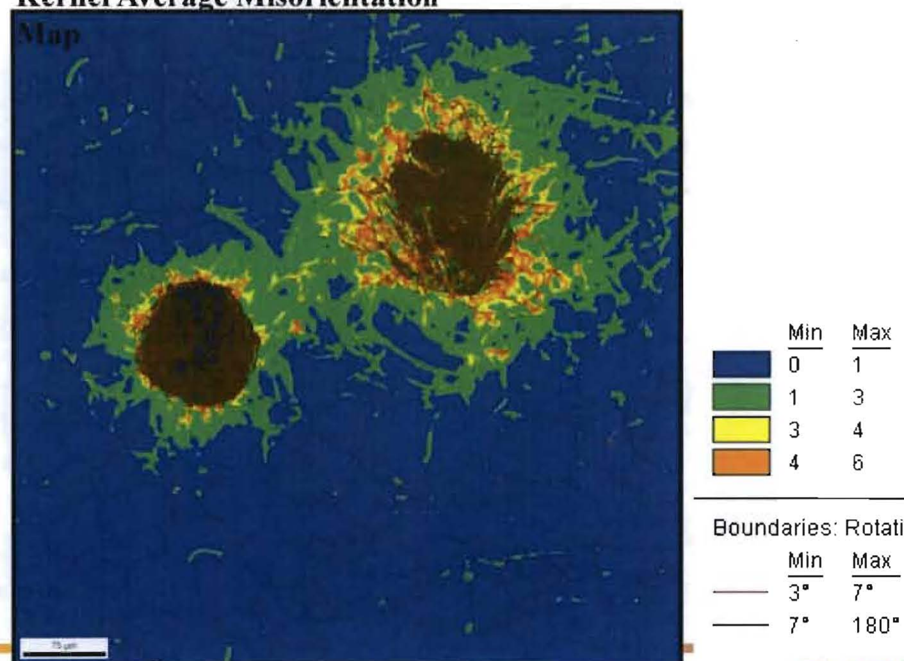




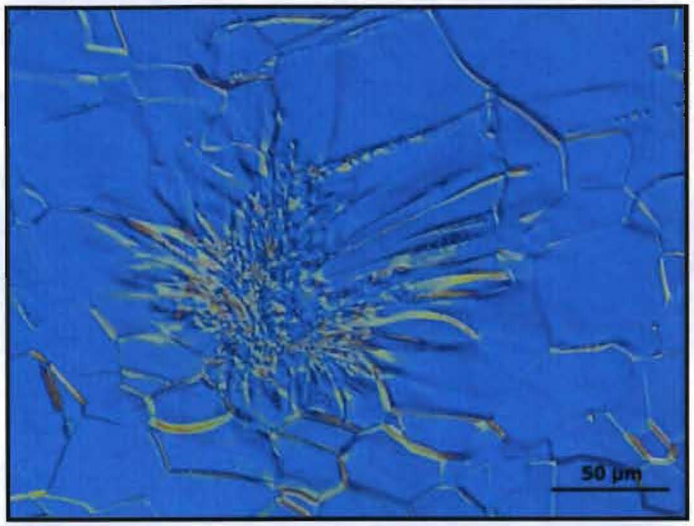
Electron Backscattered Diffraction analysis indicates:

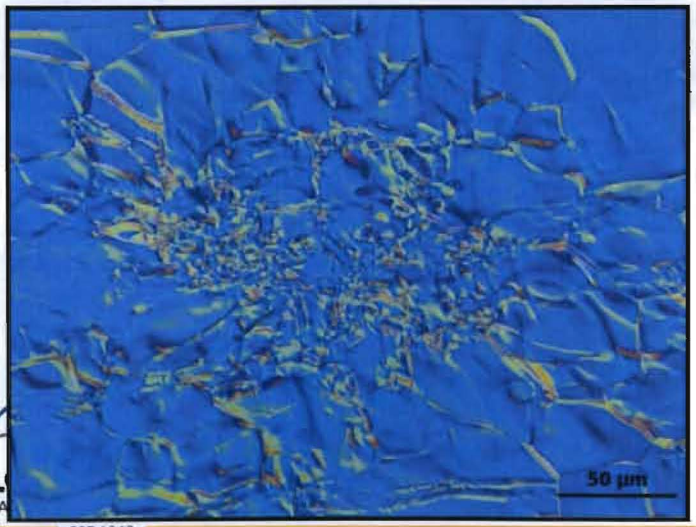
- **Strong microstructural disturbance around voids**
- **High orientation gradients affect areas extending at least on grain diameter around the void**
- **Linked deformation-affected regions extend to grain boundary network and twin boundaries surrounding voids**
- **Away from voids microstructure seems undisturbed**

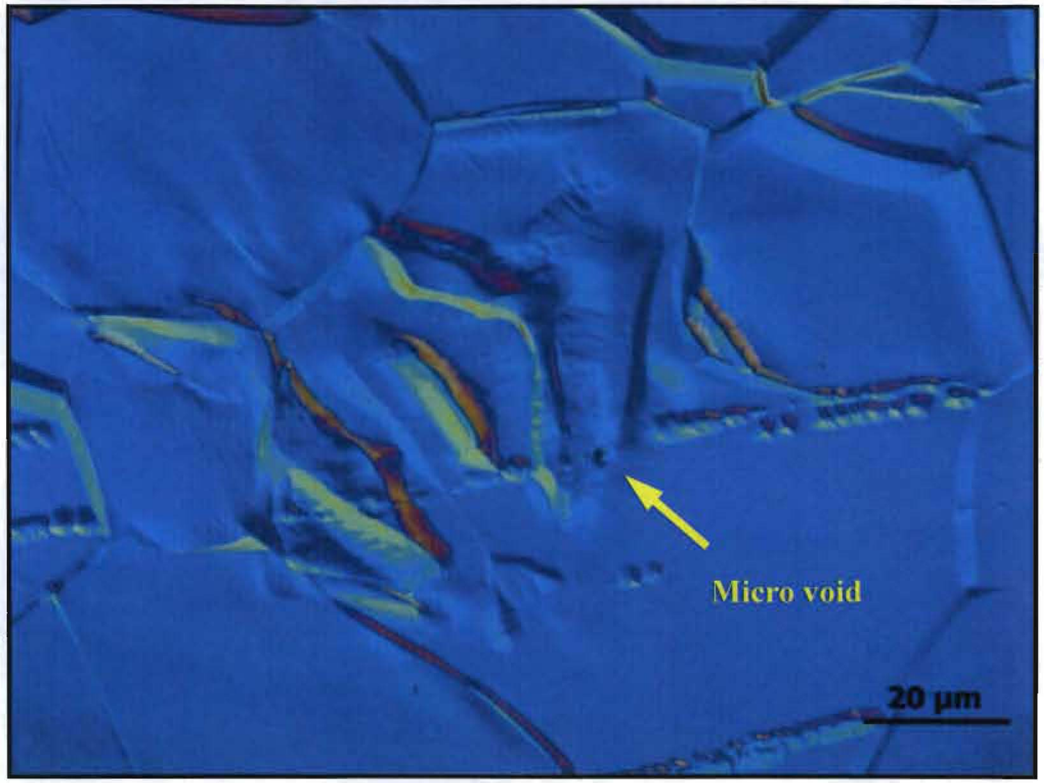
Kernel Average Misorientation Map



Aspects of Void Nucleation–Shot 2 (3.5" long, 10mm thick, 8mm HE, 1/8" foam)



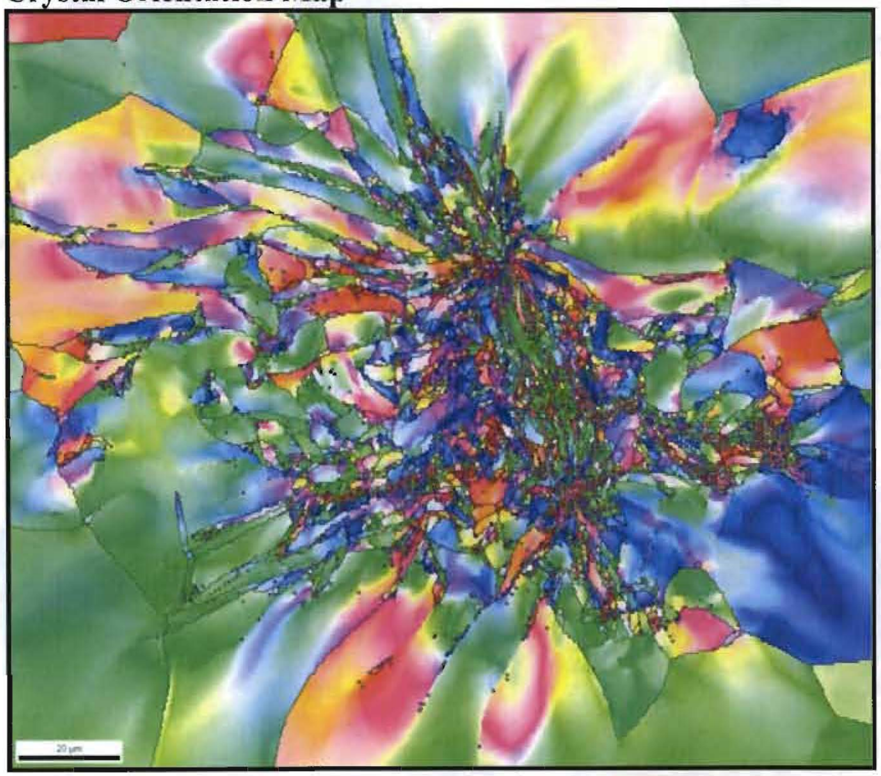




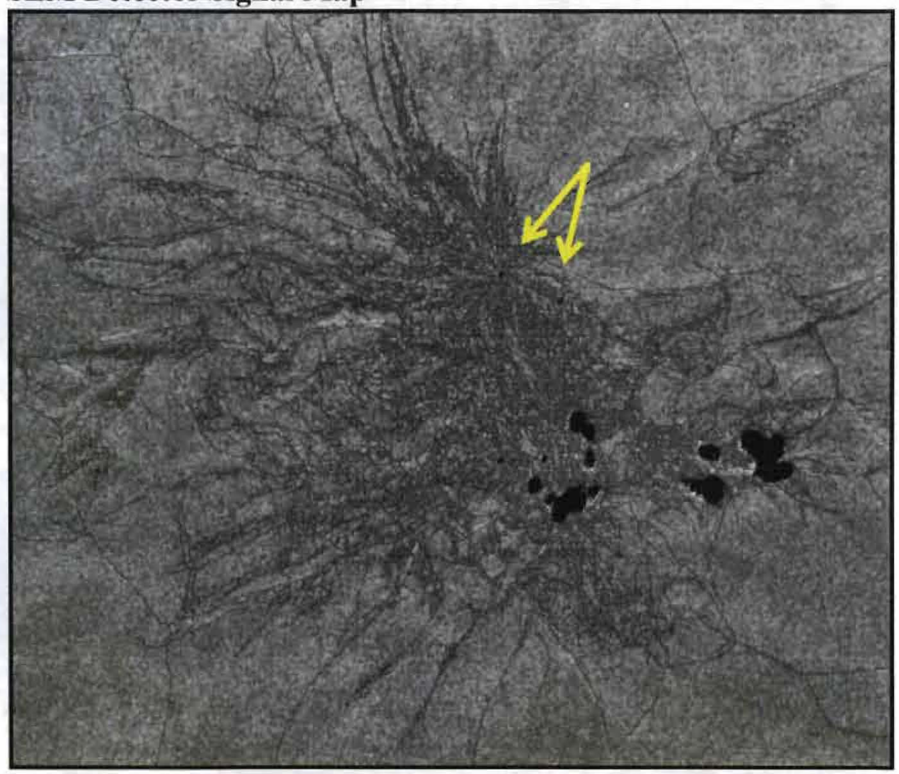
- **Damage localization extends up to 250μm, across many grains, and includes many grain boundaries, twins and microbands, offering multiple potential void nucleation sites.**

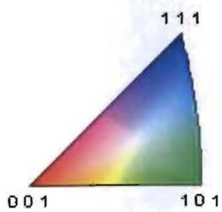
EBSD Analysis– Shot 2 (3.5" long, 10mm thick, 8mm HE, 1/8" foam)

Crystal Orientation Map



SEM Detector Signal Map





- **EBSD maps confirm that in such highly disturbed regions, with intragranular orientation gradients of up to 45°, multiple voids nucleate and grow simultaneously**
- **Question: What determines the formation of these large but still localized regions?**

Summary

• Shock loading obliquity is known to significantly alter the imposed stress tensor during shock loading-in particular the ratio of the spherical (hydrostatic) and deviatoric (shear stresses) components; this affects both shock hardening and damage evolution

• Quantification of the effects of shock prestraining on the post-shock mechanical behavior, structure evolution, and damage evolution must therefore quantify the influence of all aspects of shock loading:

- Shockwave profile shape (square, triangle, ramp, sweeping det. wave)
- Shockwave parameters (peak stress, pulse duration, rarefaction rate)
- Shockwave obliquity
- Material properties (chemistry, texture, microstructure, etc.)

• Twin formation during shock loading in Ta is seen to be a strong function of shockwave obliquity consistent with the effect of obliquity on the stress tensor.

• Electron Backscatter Diffraction (EBSD) data can only provide valuable information on twin volume fractions. Coupling with 3-D reconstruction will facilitate quantitative volume fractions.

• The concept of a "critical twinning pressure" is shown to be relevant to only pure 1-D shock loading and provides minimal insight to modeling shock effects in materials.