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Title: Influence of Sweeping Detonation-Wave Loading on Shock Hardening and Damage Evolution during Spallation Loading

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Influence of Sweeping Detonation-Wave Loading on Shock Hardening and Damage Evolution during Spallation Loading

George T. Gray III
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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 shock hardening and 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 and Will be discussed.

Influence of Sweeping Detonation-Wave Loading on Shock Hardening andDamage Evolution during Spallation Loading

George T. (Rusty) Gray III

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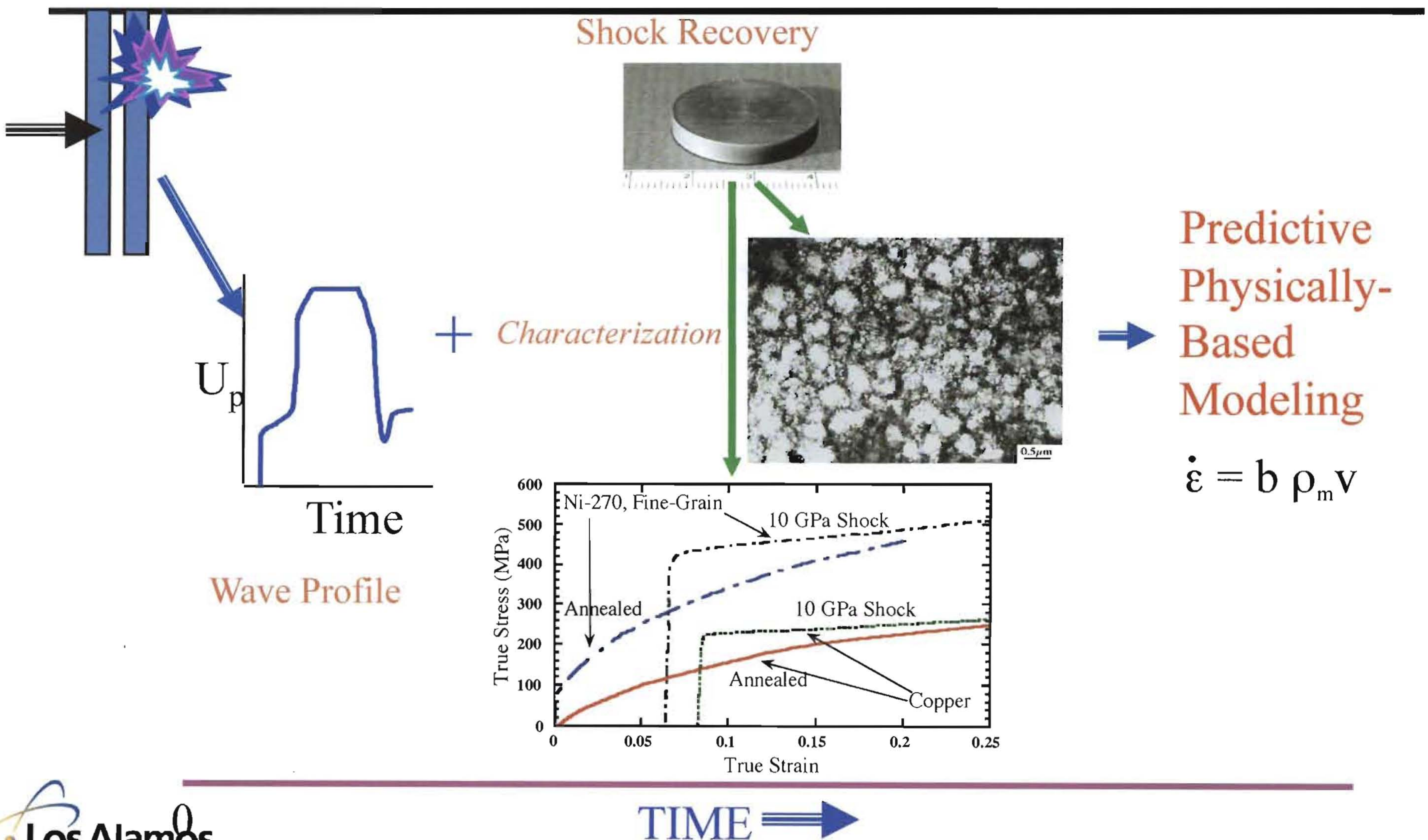
Investigation of shock loading: a question of time



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 ---

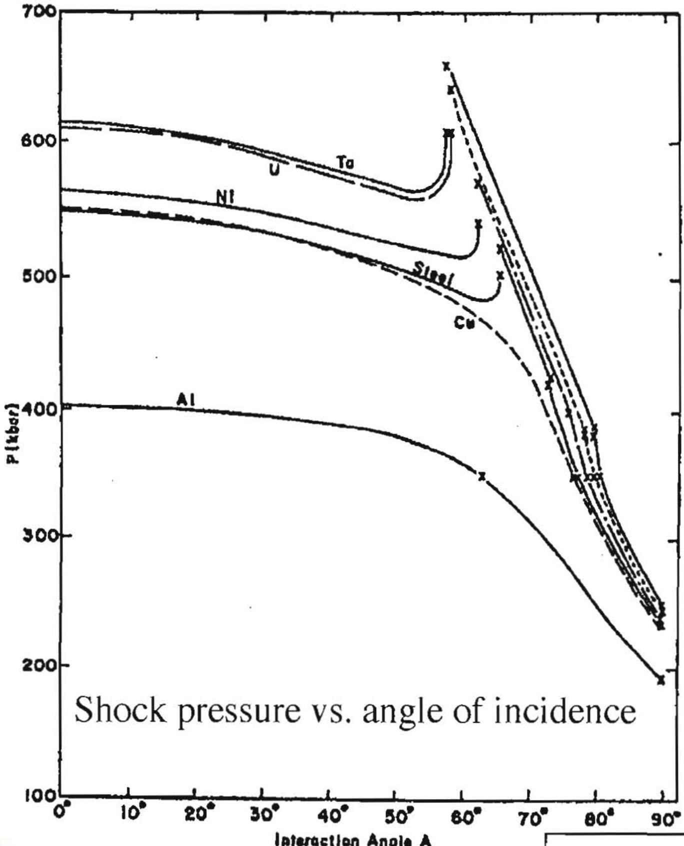
•How are defects generated and stored in each phase and how does this process differ between materials?

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



Shock pressure vs. angle of incidence

J.W. Walsh
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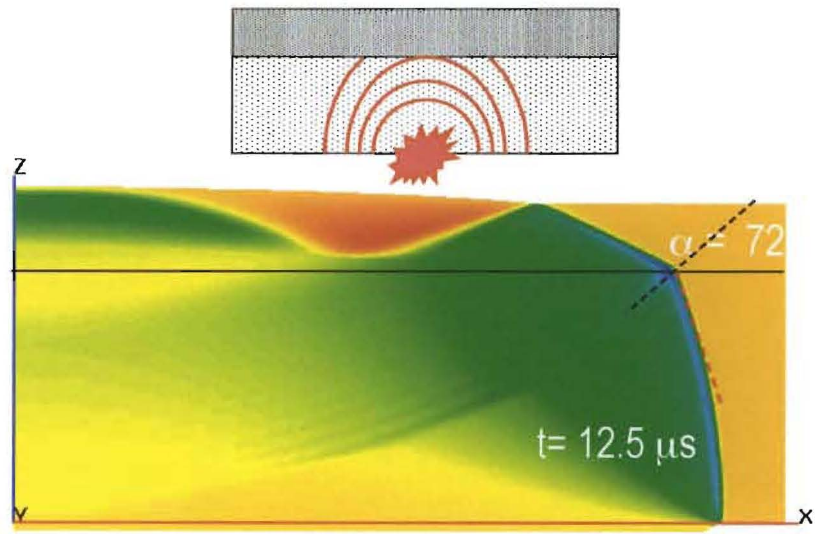


CJ pressure for
PBX 9501

T. A. Mason

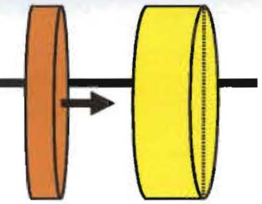
<u>Four Regimes Possible:</u> <u>just consider this from here on</u>

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

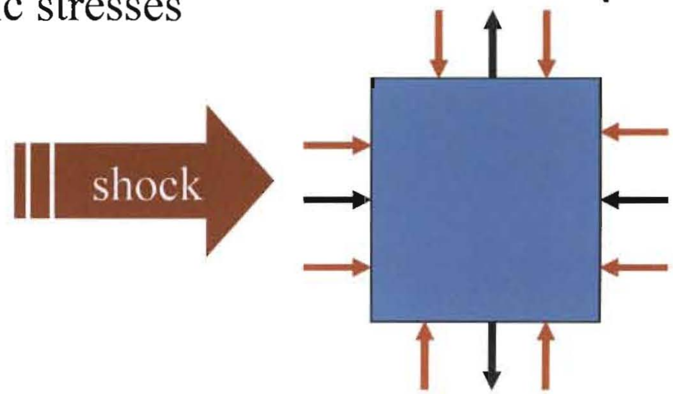
- Normal 1D shock compression/release

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



- Superimposed spherical & deviatoric stresses (loosely uncoupled)

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



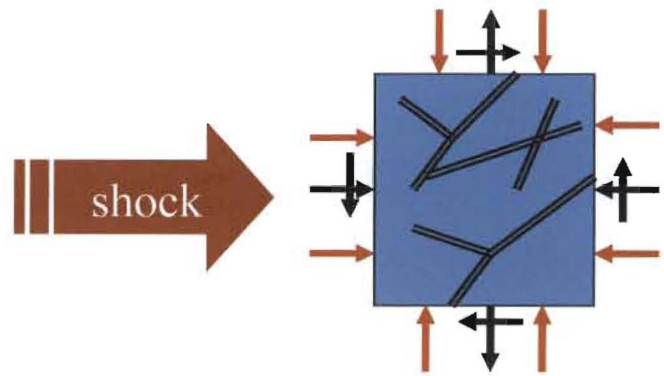
Uniform/Stable Deformation

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

Deviatoric

Spherical

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



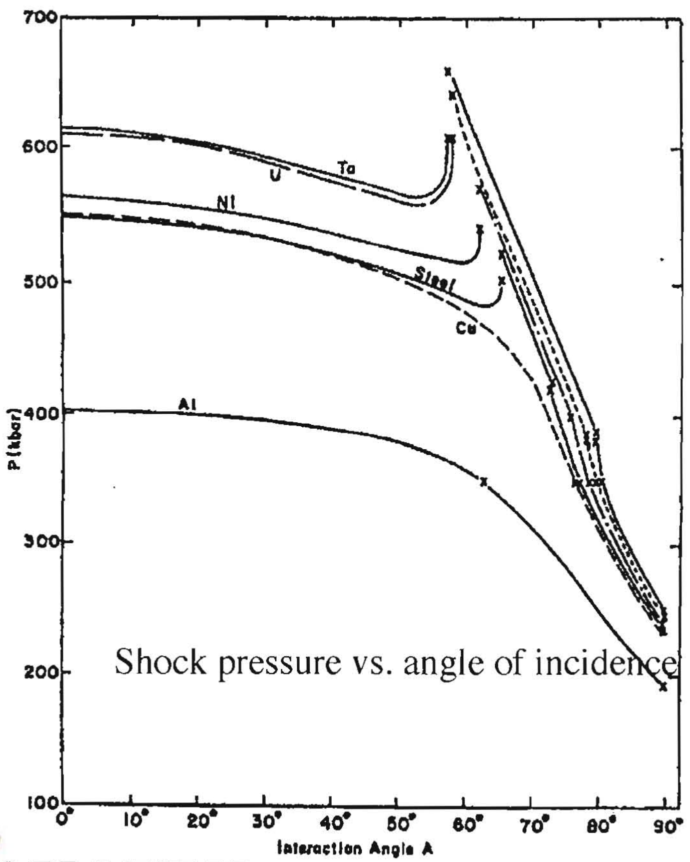
Unstable Deformation with significant shear

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



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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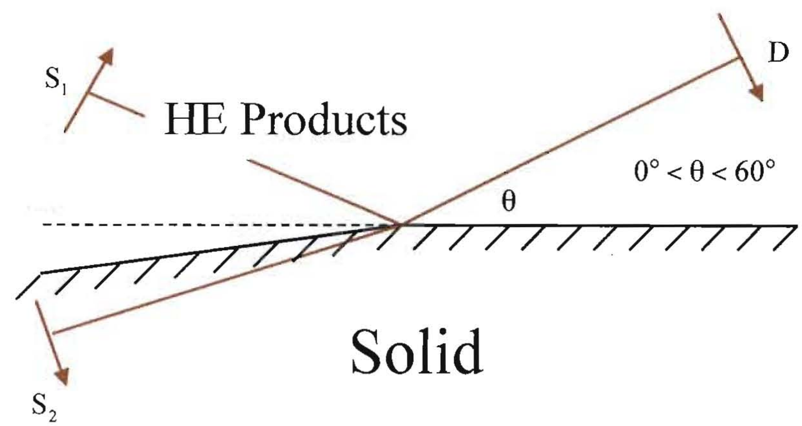
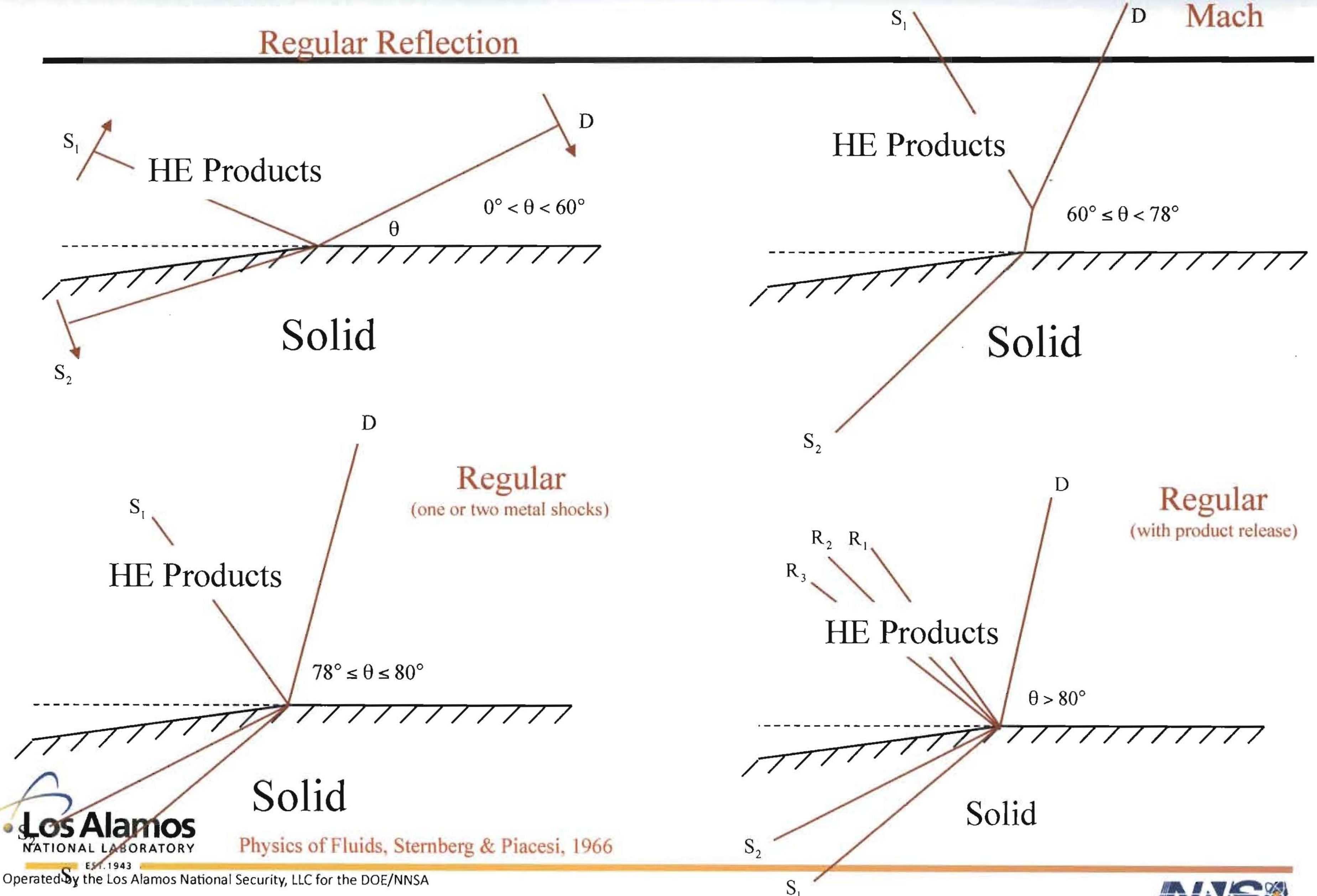


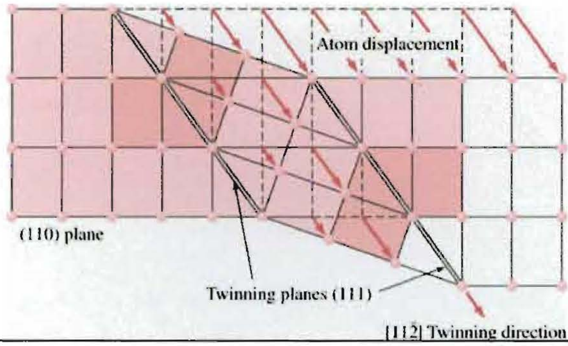
Oblique Reflection Wave Structures

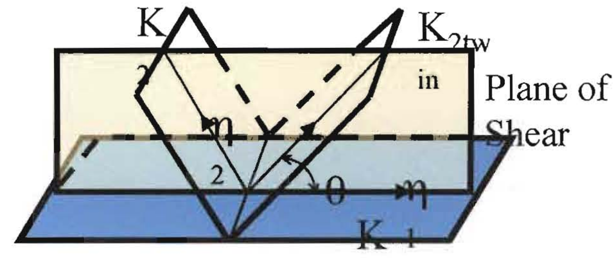


Physics of Fluids, Sternberg & Piacesi, 1966

Deformation Twinning

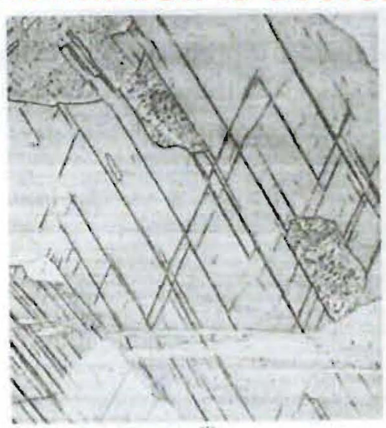
Twin initiation or growth occurs when the externally applied shear stress across the K_1 plane, resolved in the ω_1 direction, reaches a "critical" value.





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.

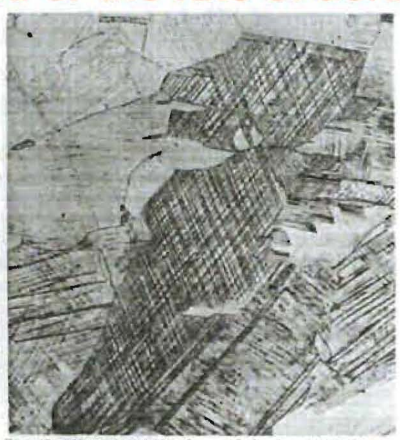


Fig. 13—Microstructure of annealed α brass (31.40 pct Zn) after 550-kbar shock. X250.

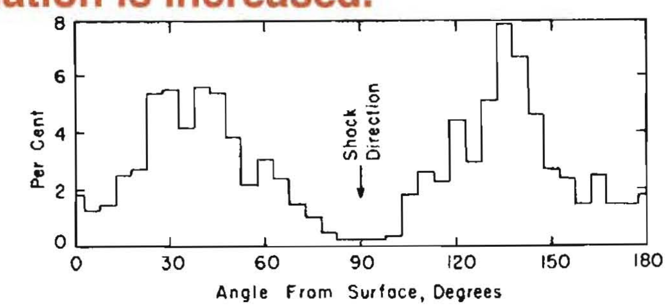


Fig. 14—Angular frequencies of markings on brass after 550-kbar normal shock. Plane of section includes shock direction.

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

Twinning during shock loading: A complex series of differing observations

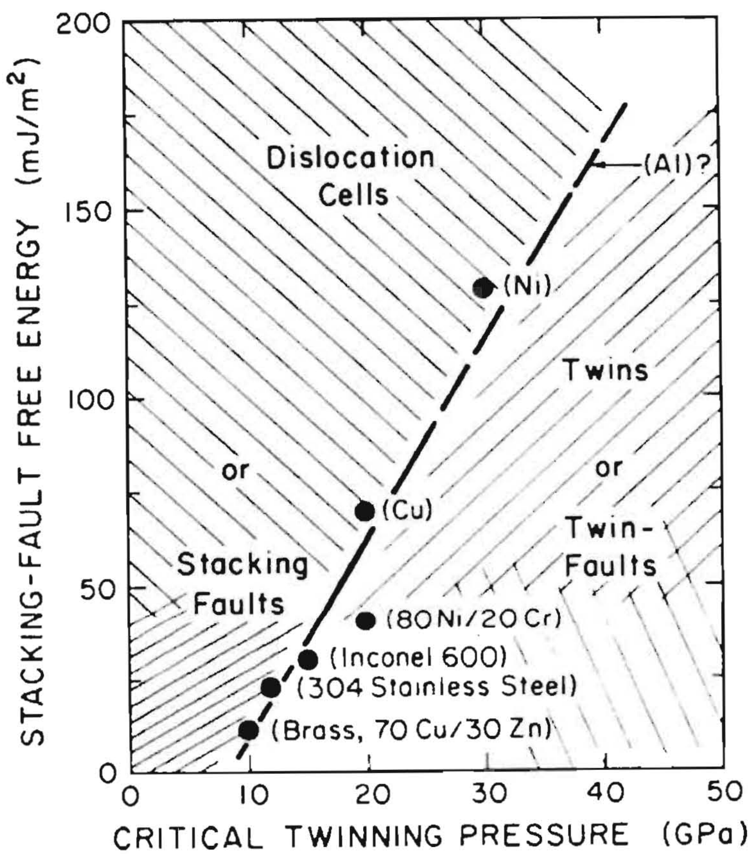


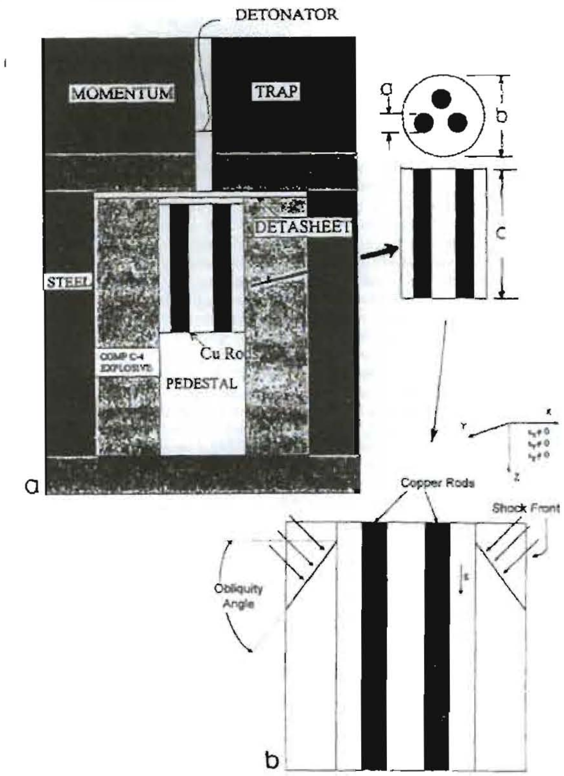
FIG. 1.15: *Stacking-fault free energy versus critical twinning pressure (for initial twinning in [001] directions) for a number of FCC metals and alloys where the residual strains were very small or negligible (<1%), and* $\Delta t = 2\mu s$, *i.e. the shock pulse duration shown in Fig. 1.7 was constant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

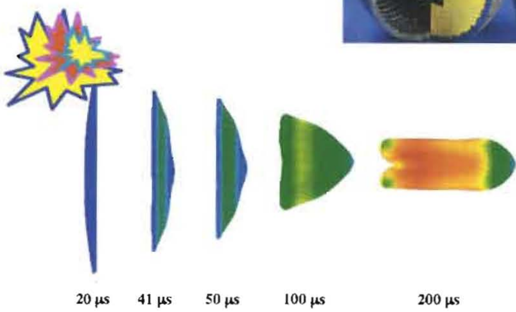
"There was no evidence of these features in any of the Ta EFP's. Since shock-waves of higher peak pressures than necessary for plane-wave shock induced twinning are involved in EFP formation it is believed that the actual, dynamic deformation process either retards or annihilates deformation twins."

Effect of HE-Shock Driven Shock Prestraining on Materials

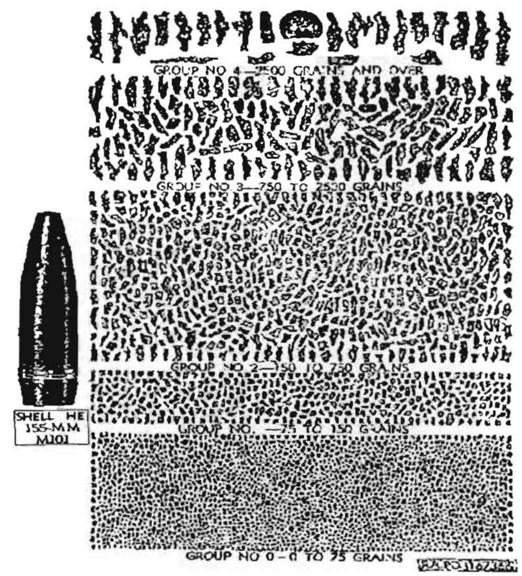
Constitutive Response of Warheads / weapon materials are preconditioned by HE preshock load cycle.

↓

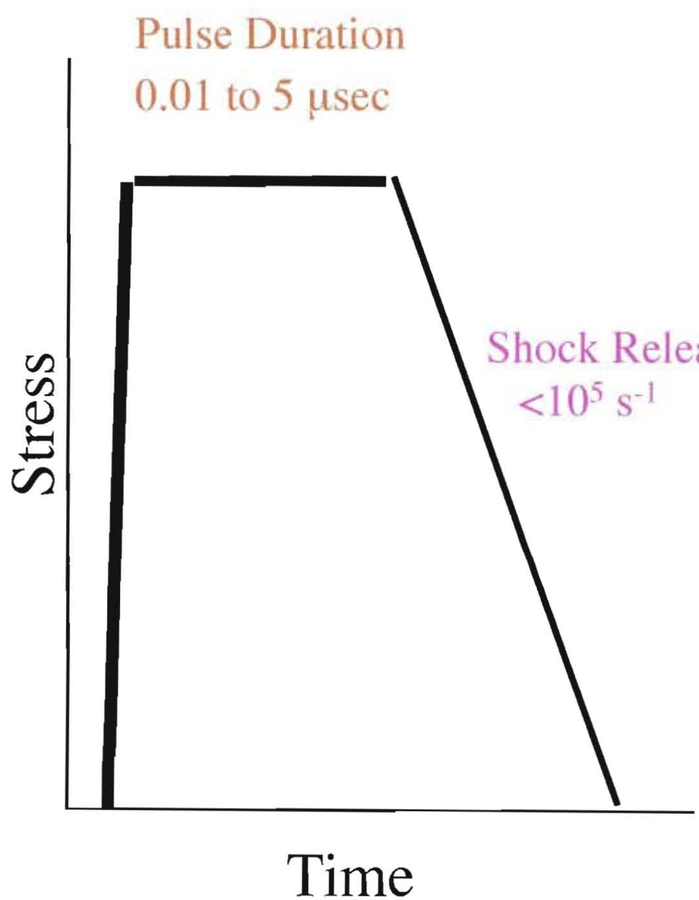
Predictive Performance of Warhead requires knowledge of shock hardening



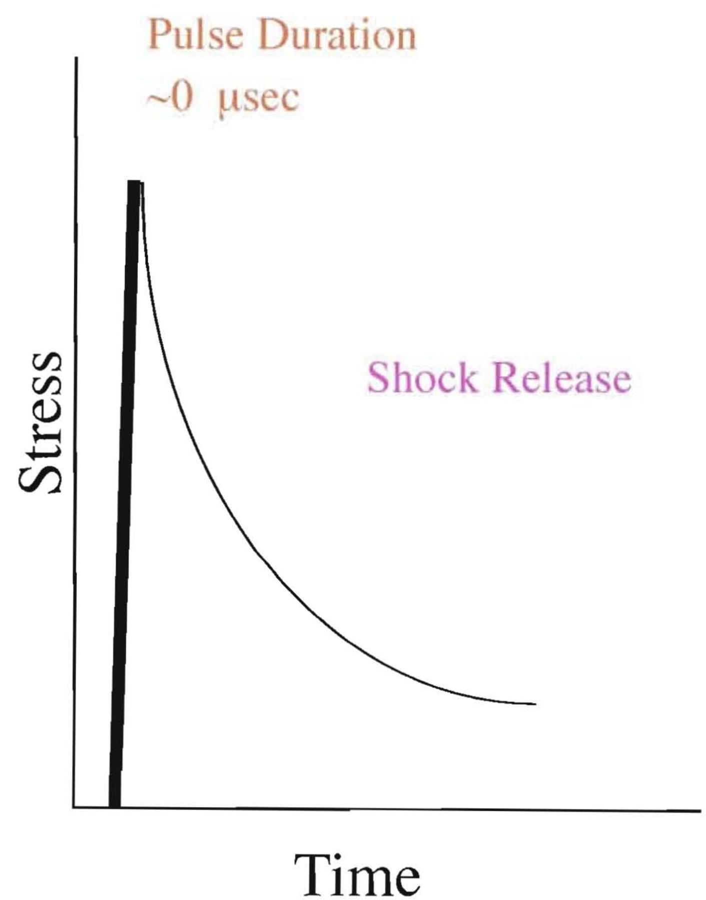
Liners / warheads



Shock-Wave Prestrain - Flyer Plate vs. Taylor Wave



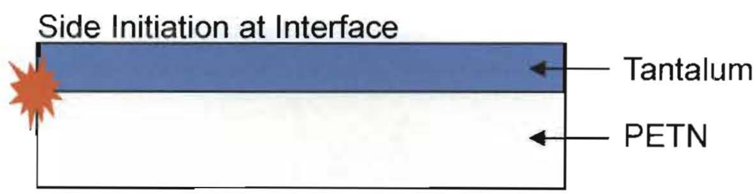
Flyer-Plate

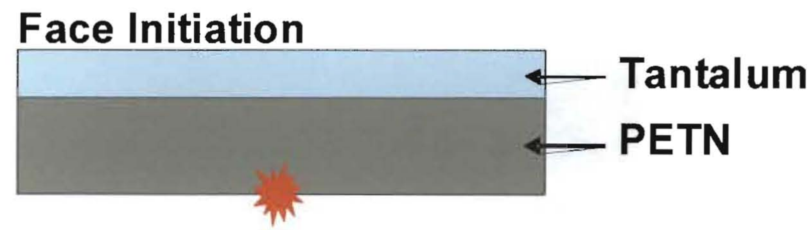


Energetic-Taylor Wave

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:*



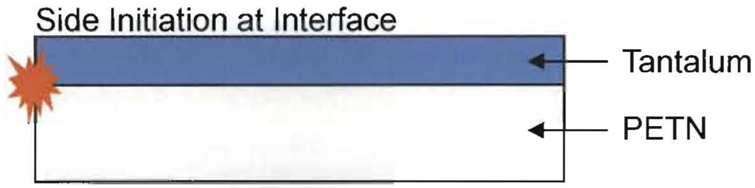


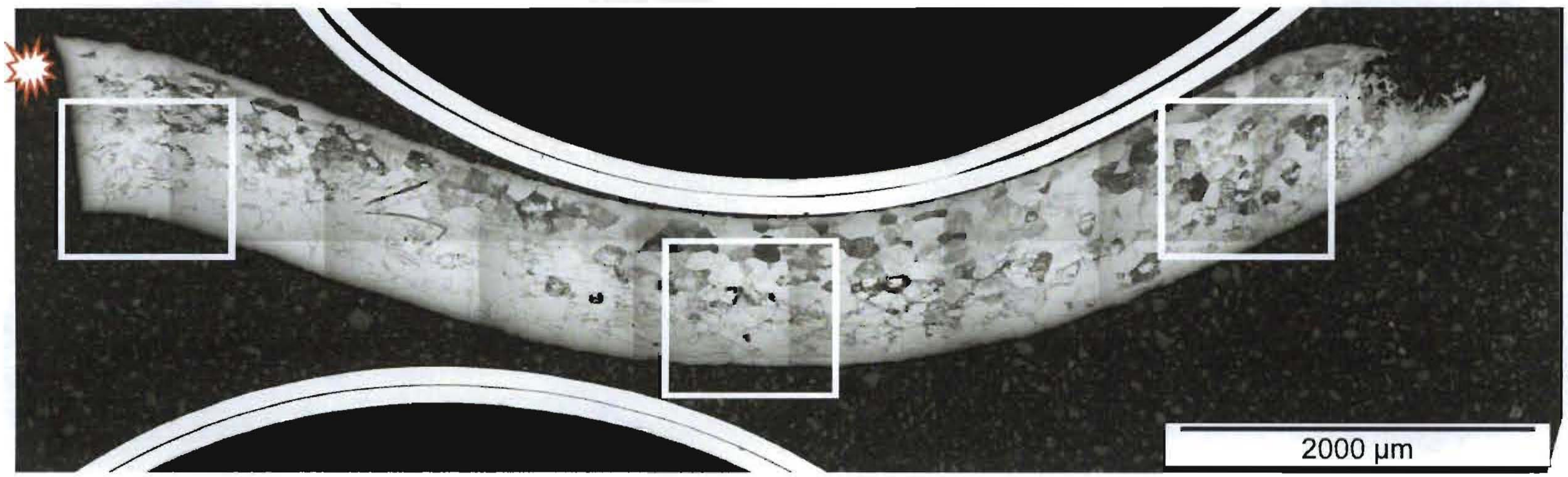
EBSD analysis:

- *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

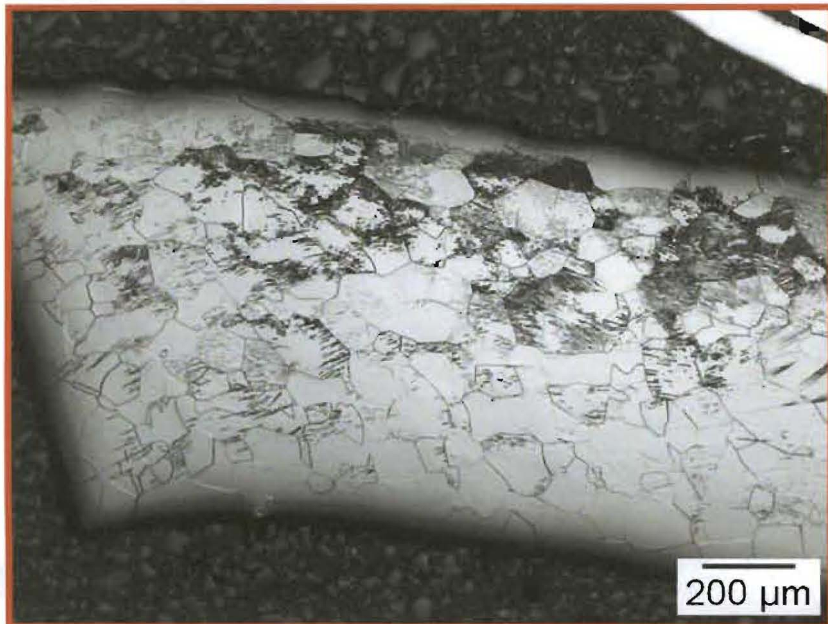




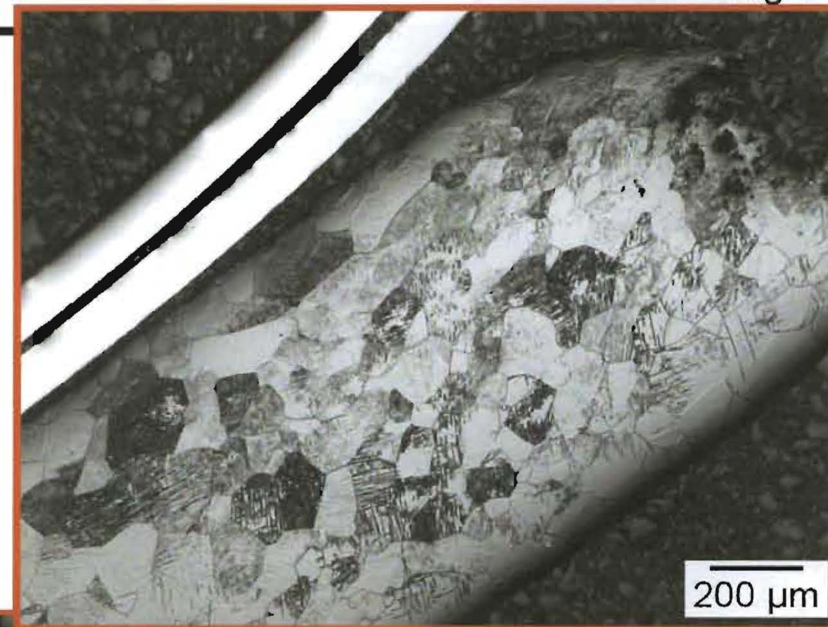
- Qualitatively, the amount of twinning increases from left to right, with a visibly higher concentration along the upper edge. (adjacent to HE)
- Red rectangles and twin close-up images are shown at larger scale on the next slide.

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

Left



Right



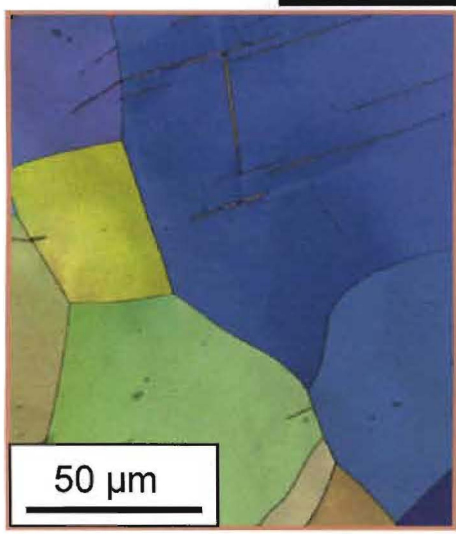
Center

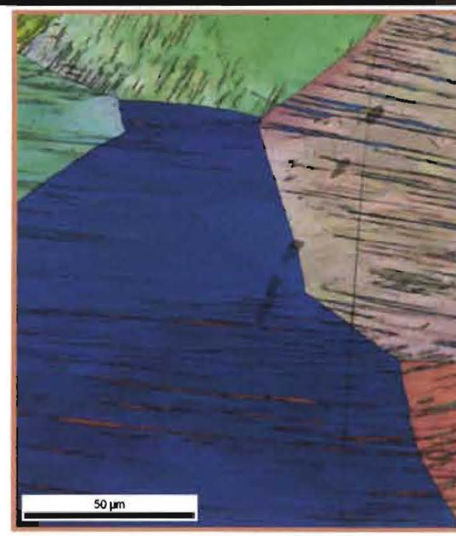
50 µm

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

50 µm

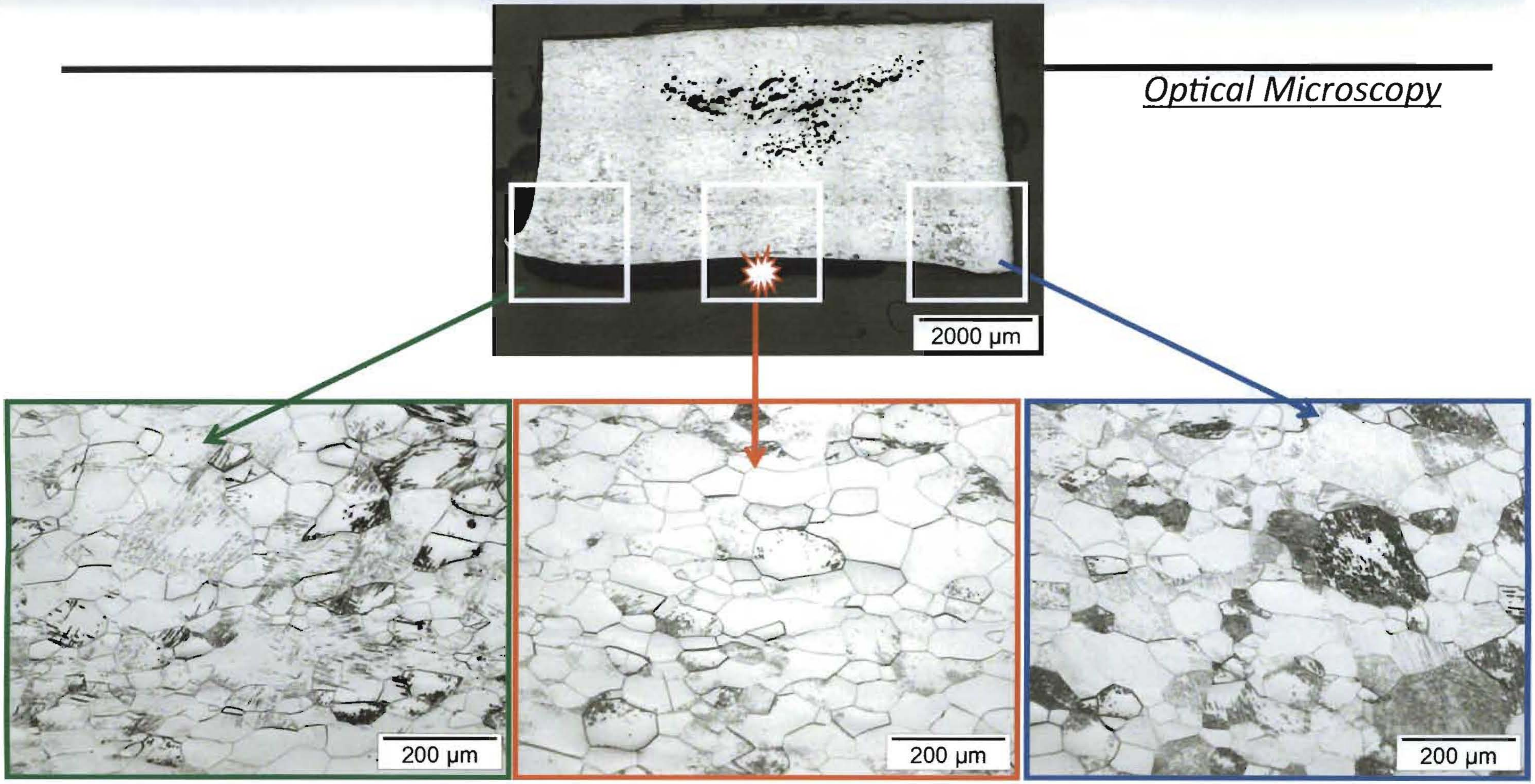
	Bottom Left	Bottom Center	Bottom Right
Avg. twin fraction	**0.21**	**0.47**	**0.52**





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

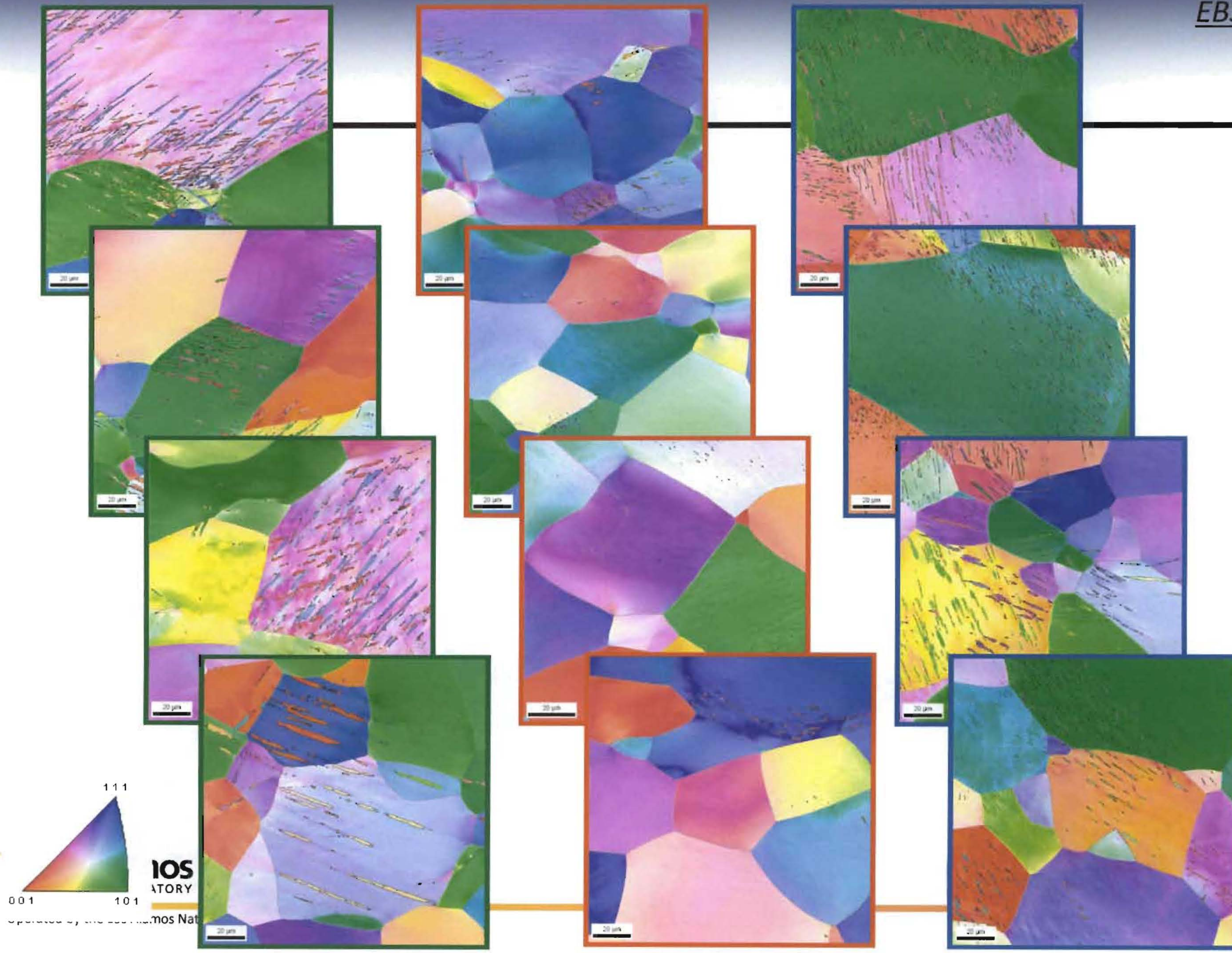
Center-Detonated Ta sample



- *Twinning appears more profuse in the bottom corners*
- *Contrast not as strong as in the case of the disc (smaller sample)*

EBSD

Left Bottom | Center Bottom | Right Bottom

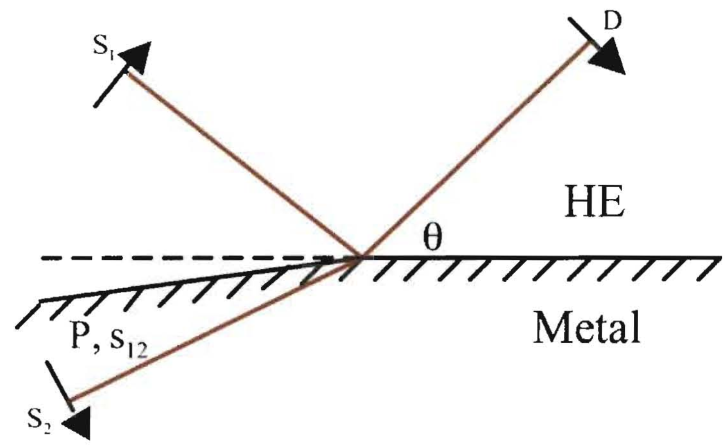


Modeling of Oblique Shock Loading of Ta

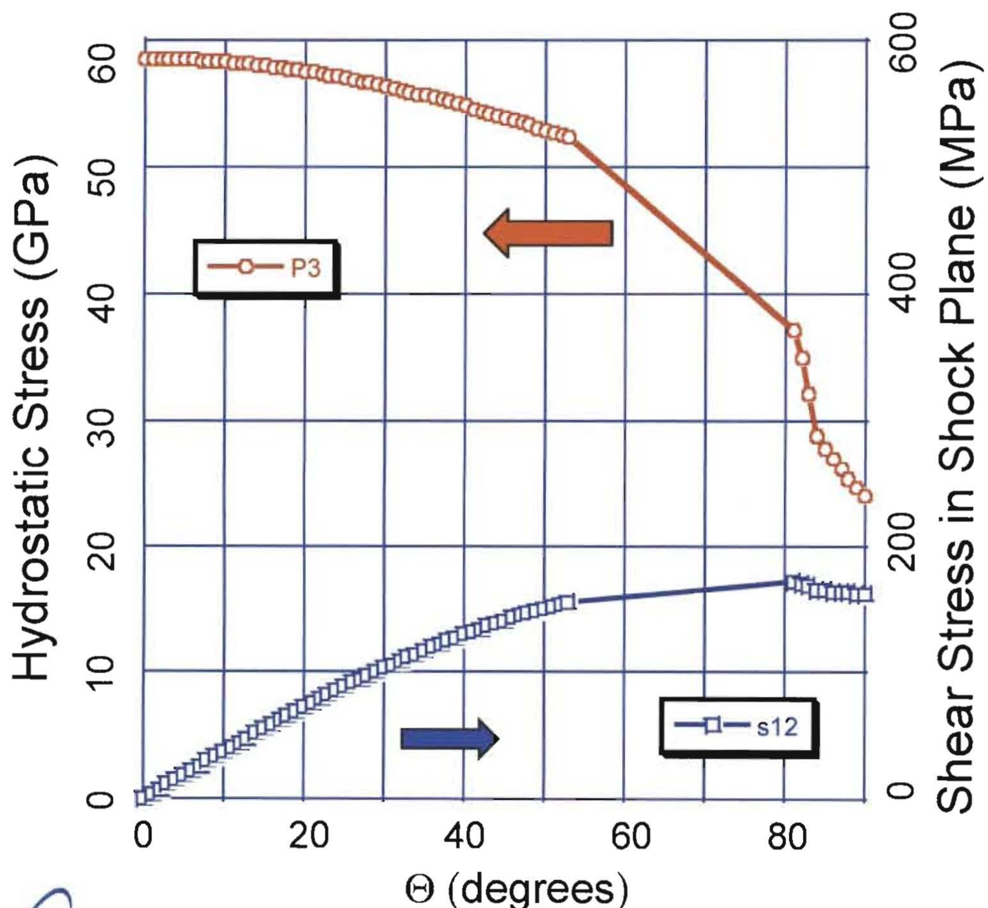
- Consider the interaction of an oblique detonation wave (D) with a PETN/metal interface as depicted by the right-going regular-reflection wave structure.

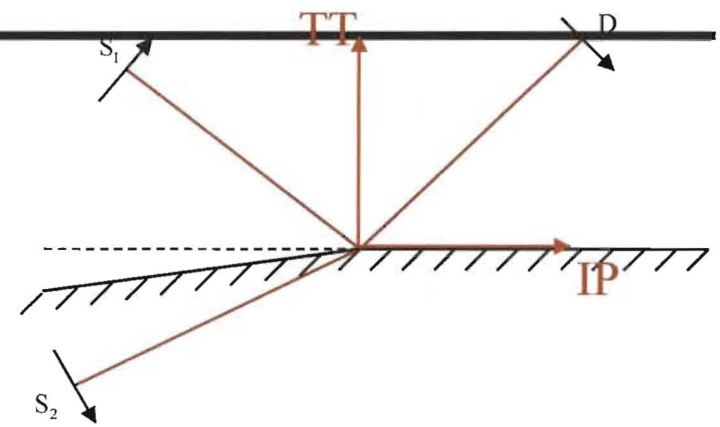
- The wave D propagates into non-reacted HE at an angle of obliquity defined by θ , with D reflecting from the interface as a gas shock into HE combustion products and transmitting shock into the Ta metal.

- 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

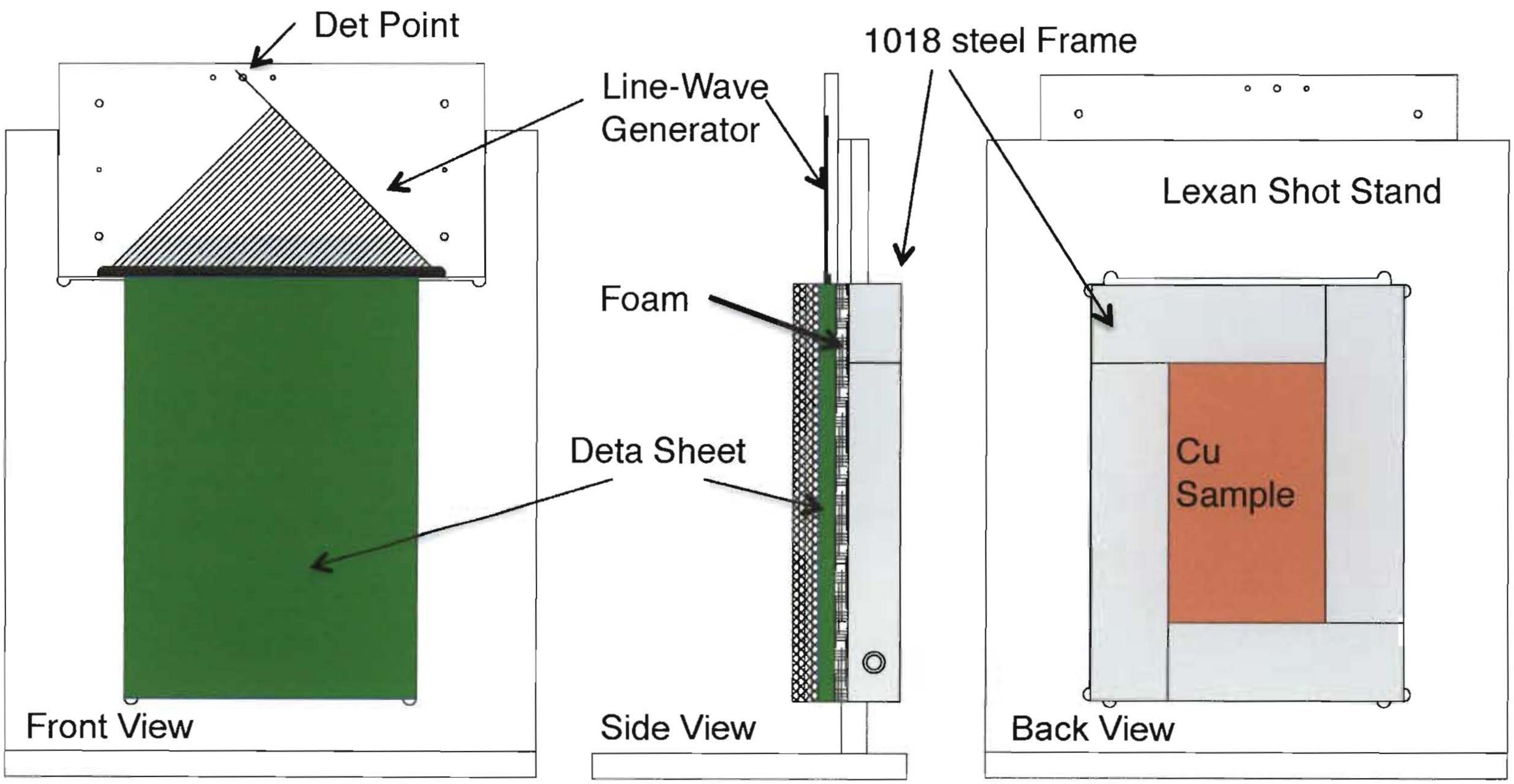




Two sources of shear possible:

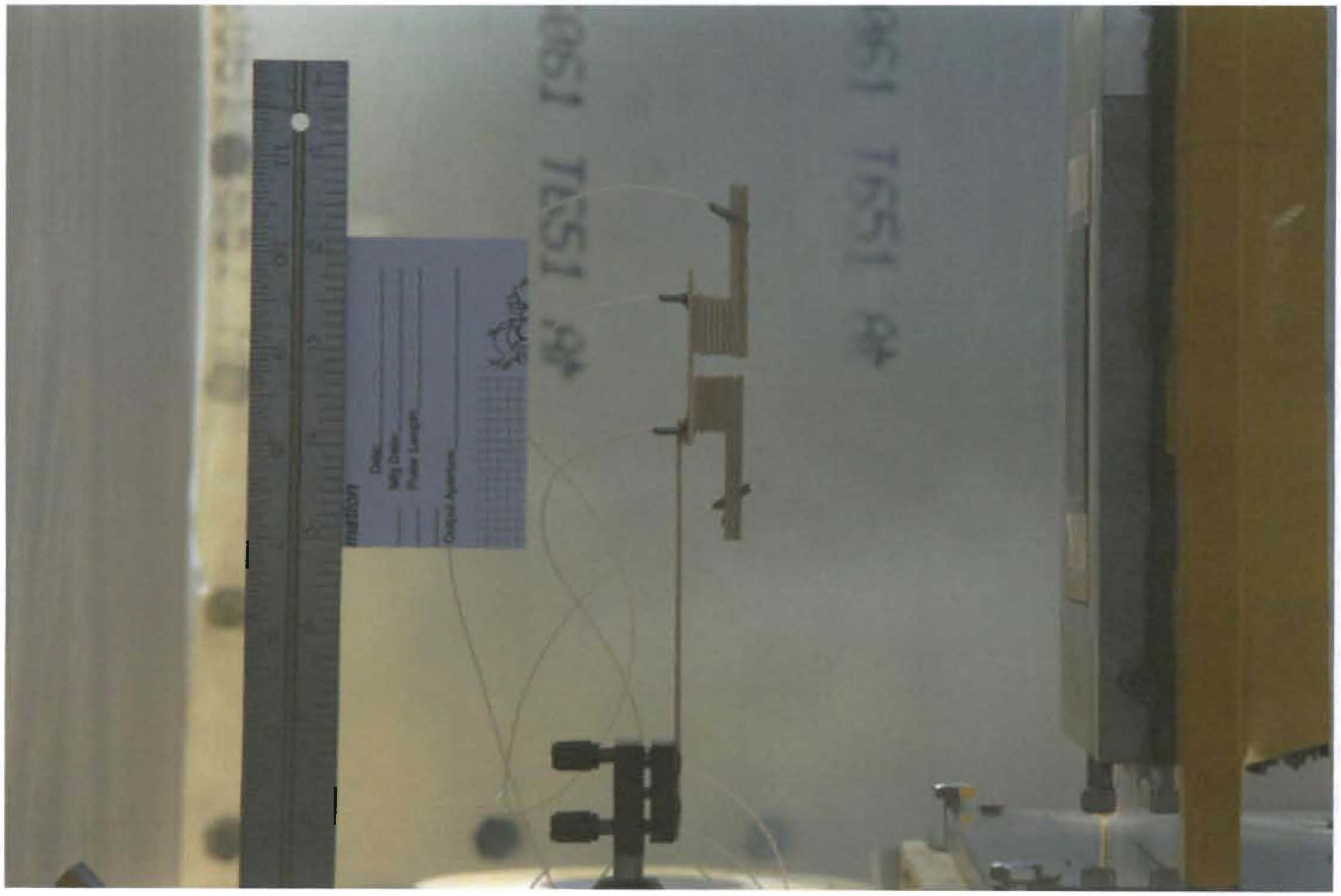
1) Change of ref frame from Shock to Lab
2) Induced shear from material anisotropies

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



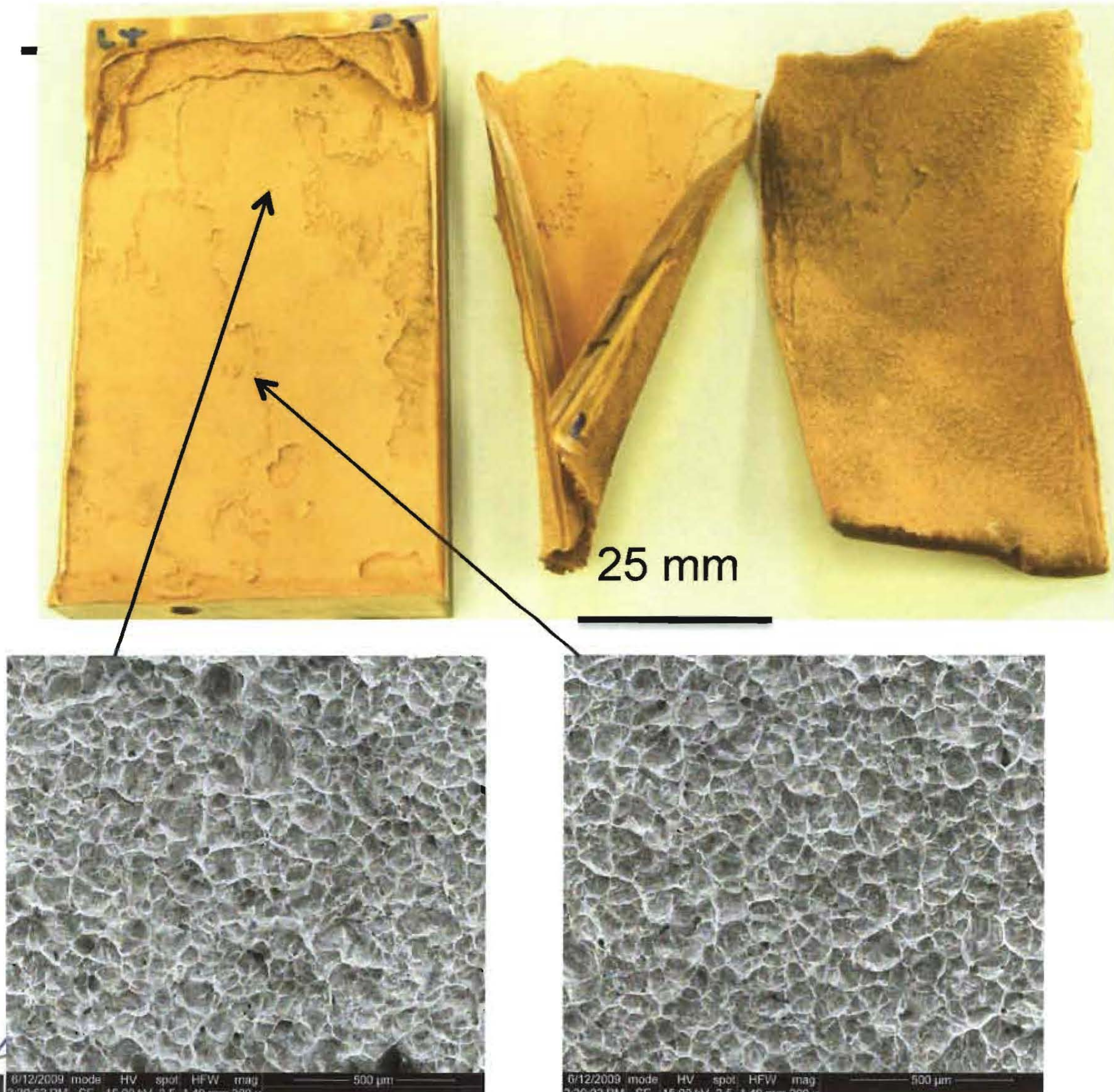
Sweeping Detonation-Wave Experimental Set-Up

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



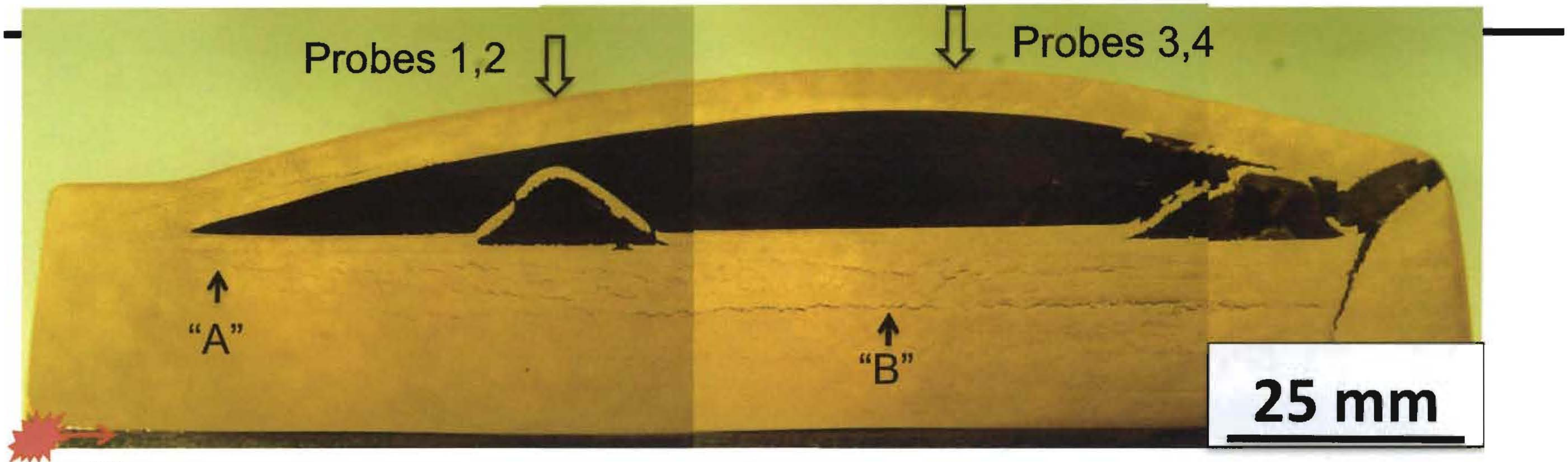
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

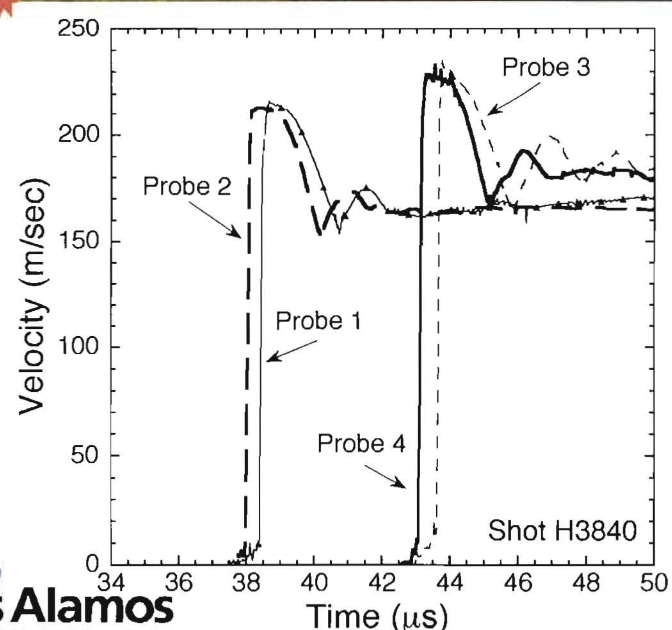
Sweeping Detonation Drive: 4 mm Detasheet in direct contact

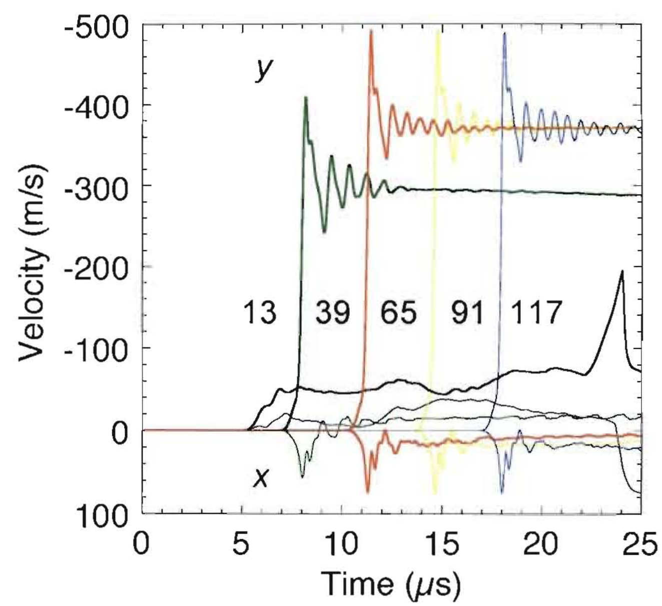


- The damage evolution is seen to consist of equiaxed ductile dimples consistent with a Mode I overload fracture process
- No evidence of shearing in the dimples was observed

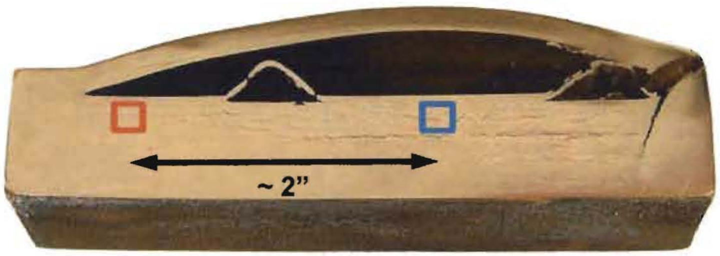
Sweeping Detonation Drive: 8 mm Detasheet + 6.35mm Foam

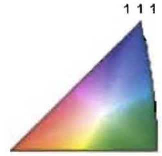


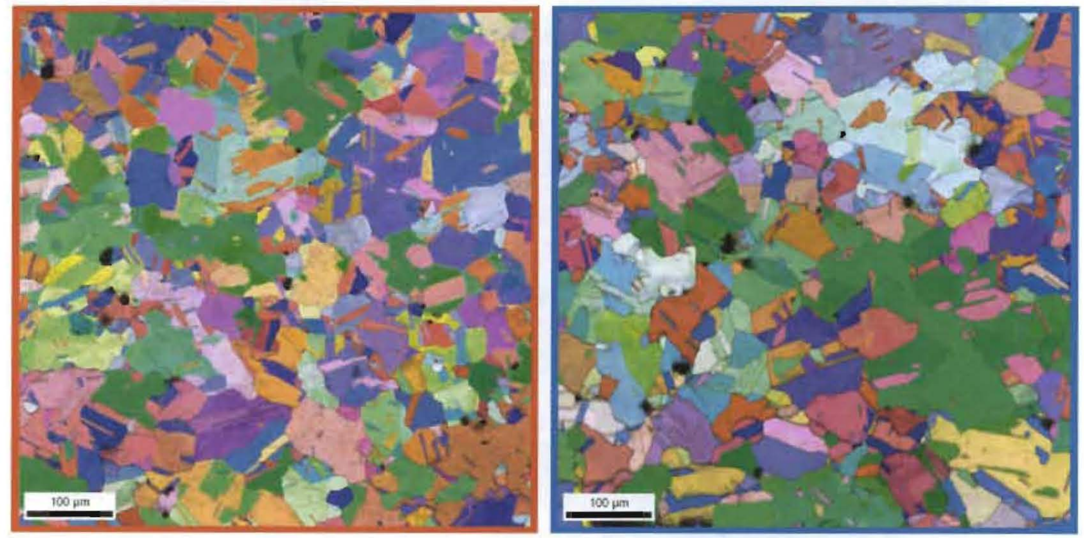




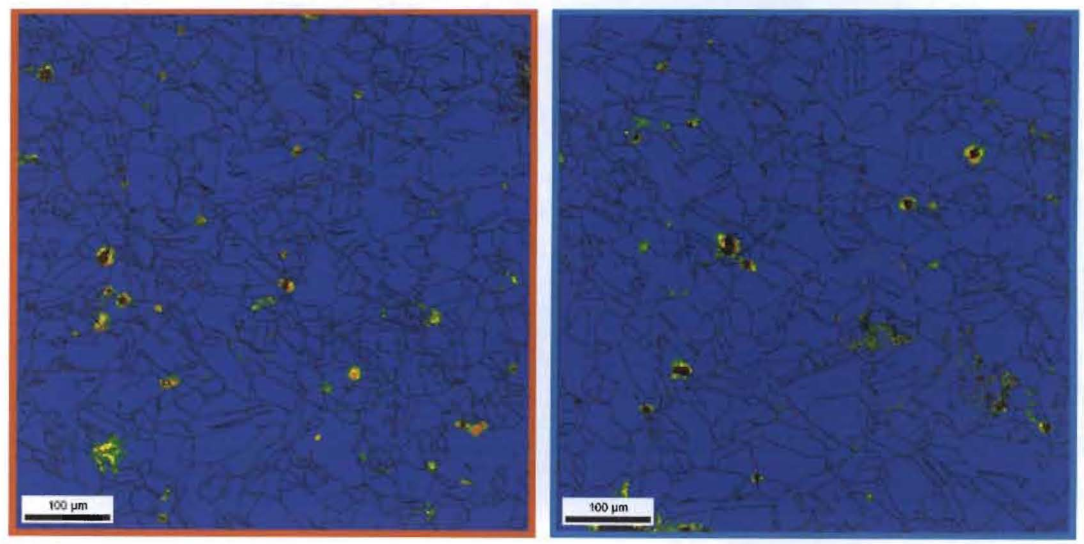
EBSD Analysis



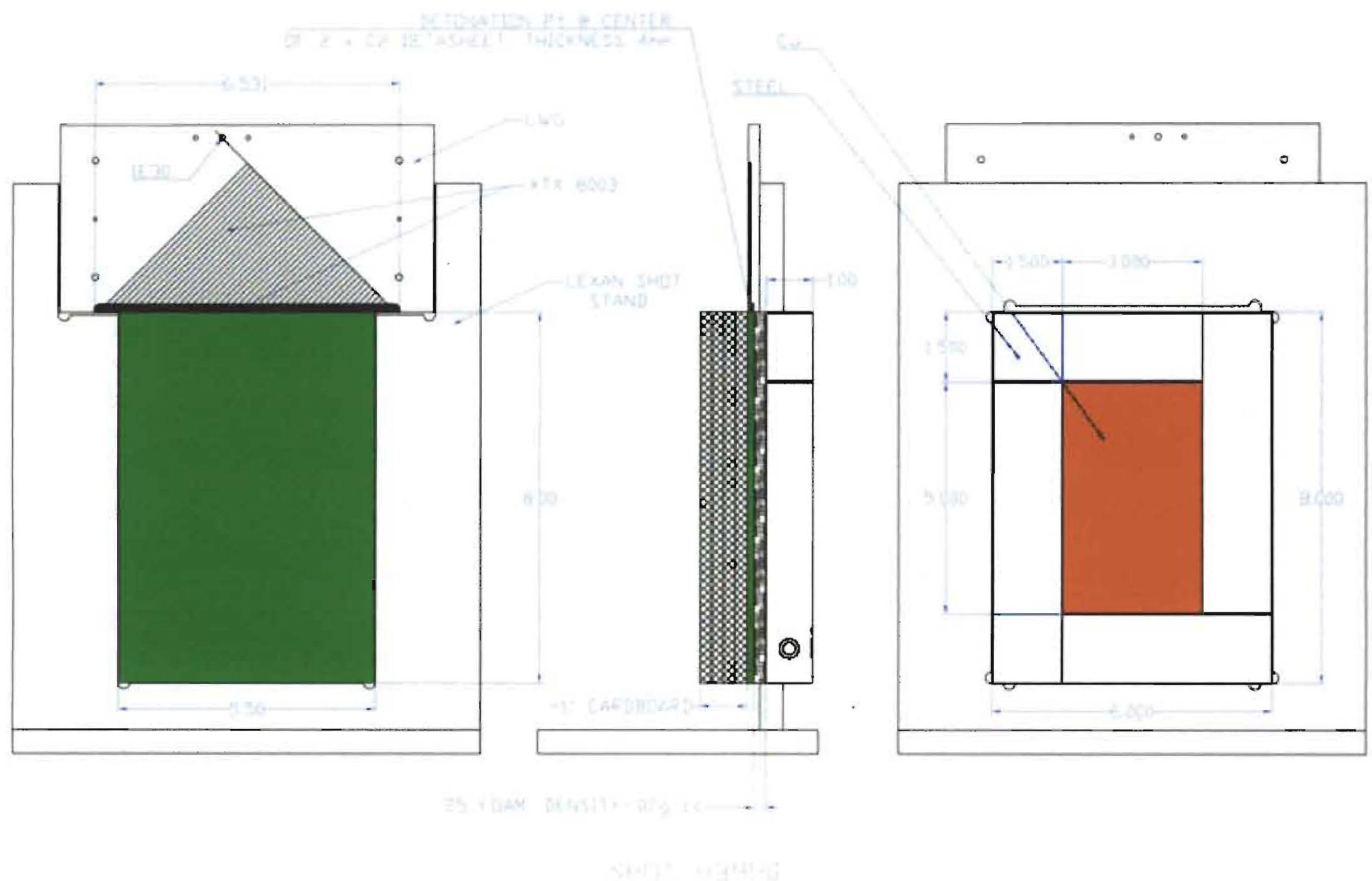




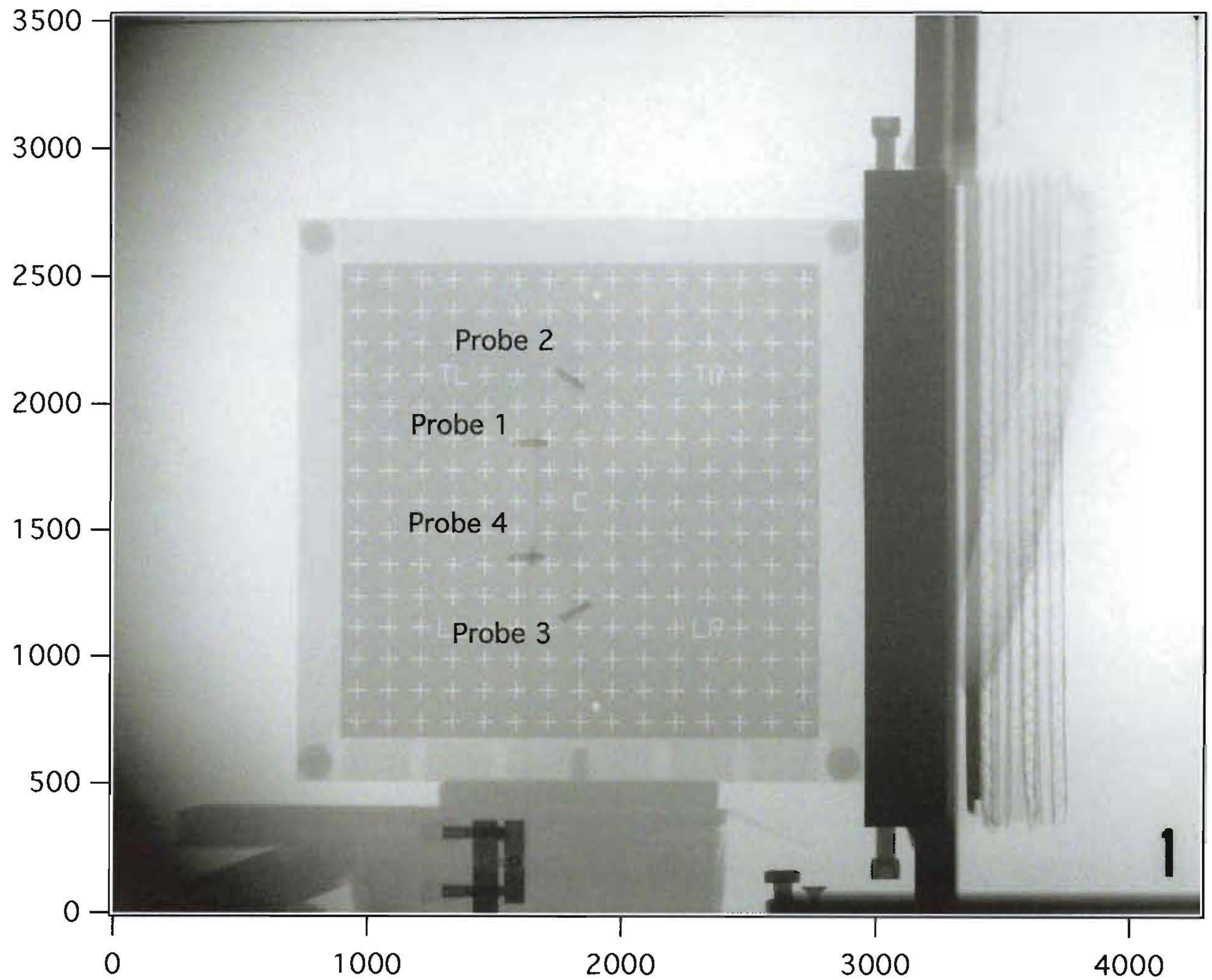
- No obvious shock obliquity effects
- No deformation twins detected
- Kernel average misorientation maps are similar



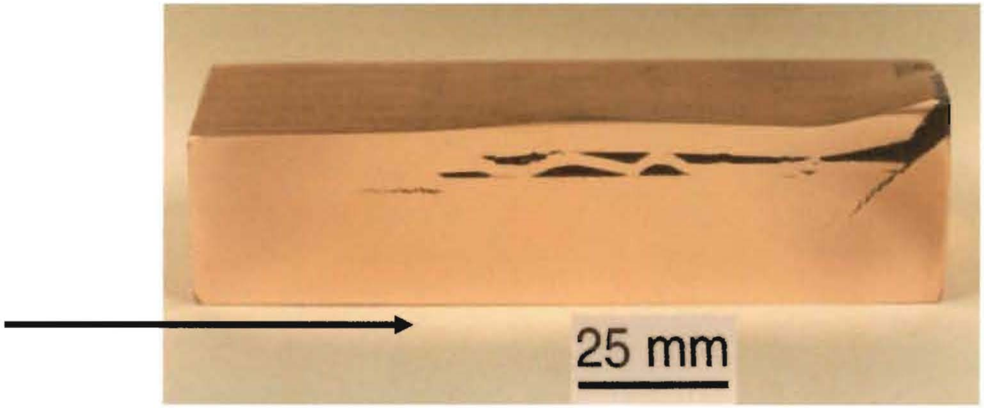
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

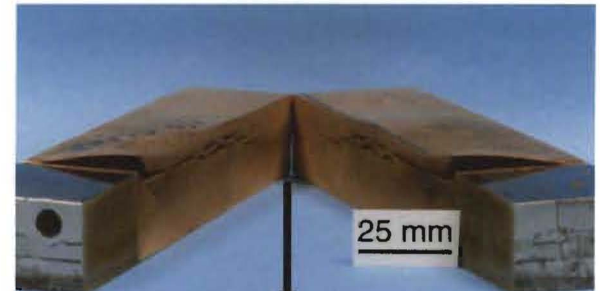


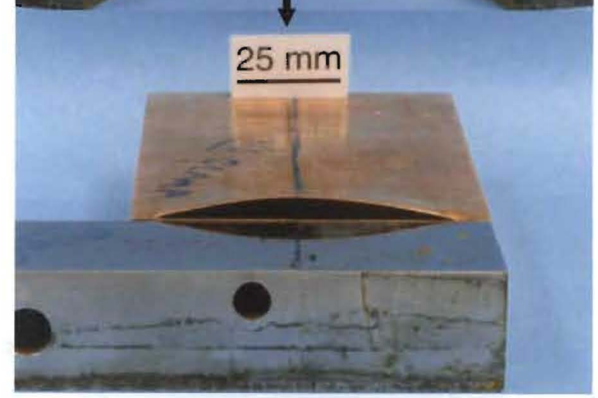
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

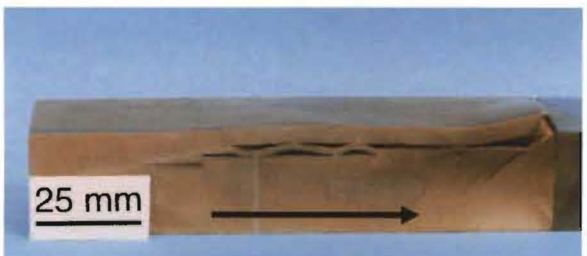


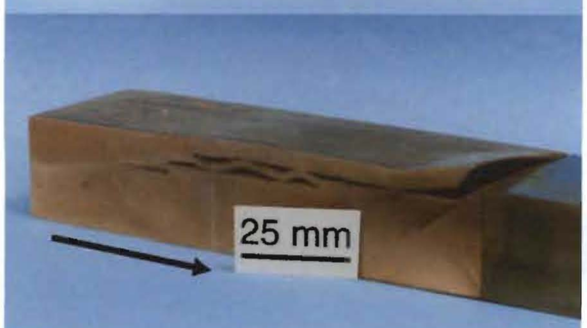
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

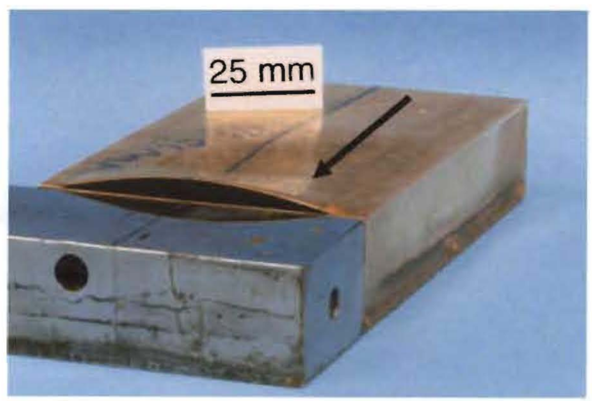


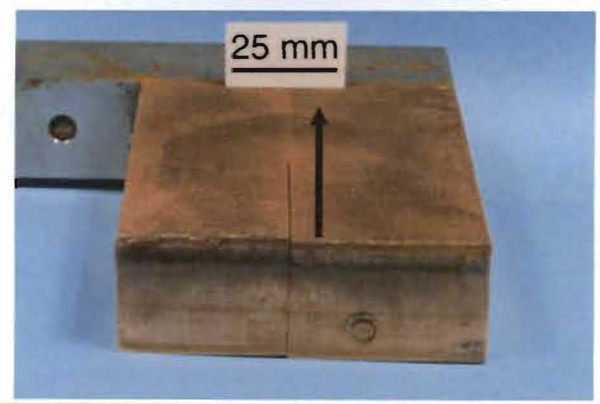




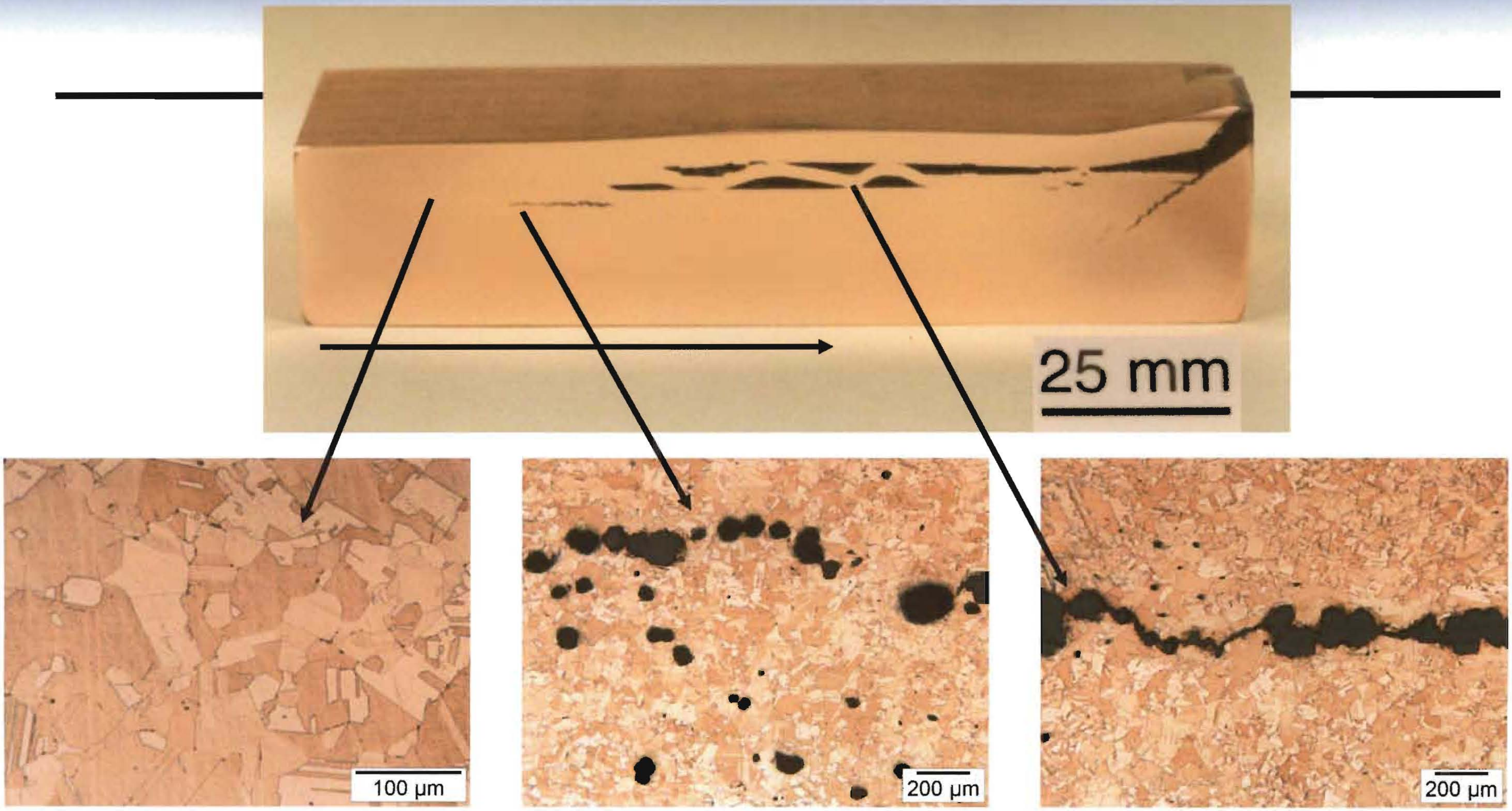




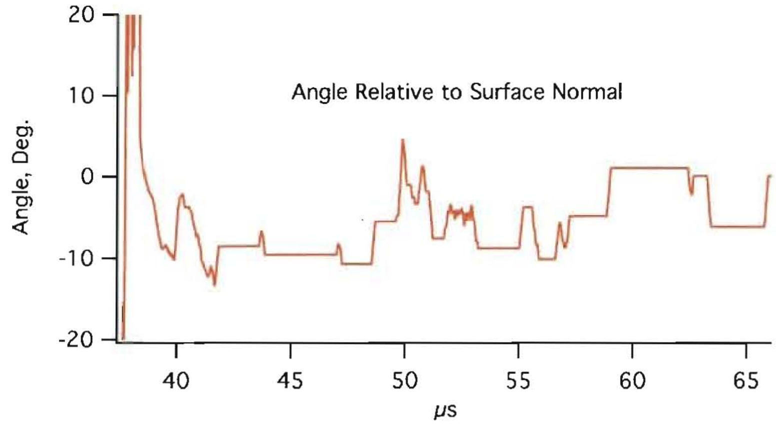


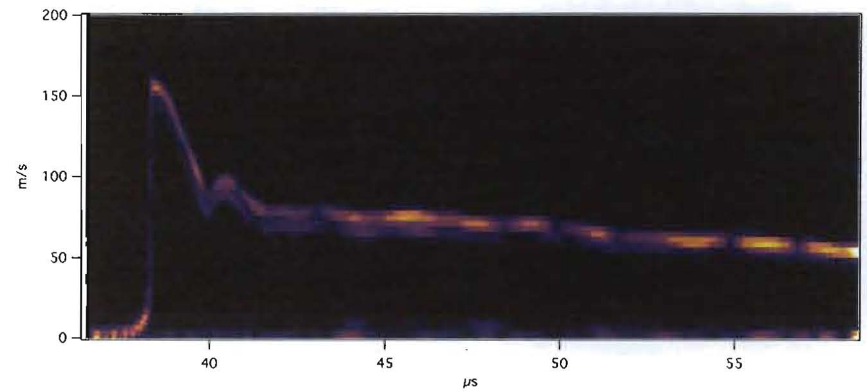


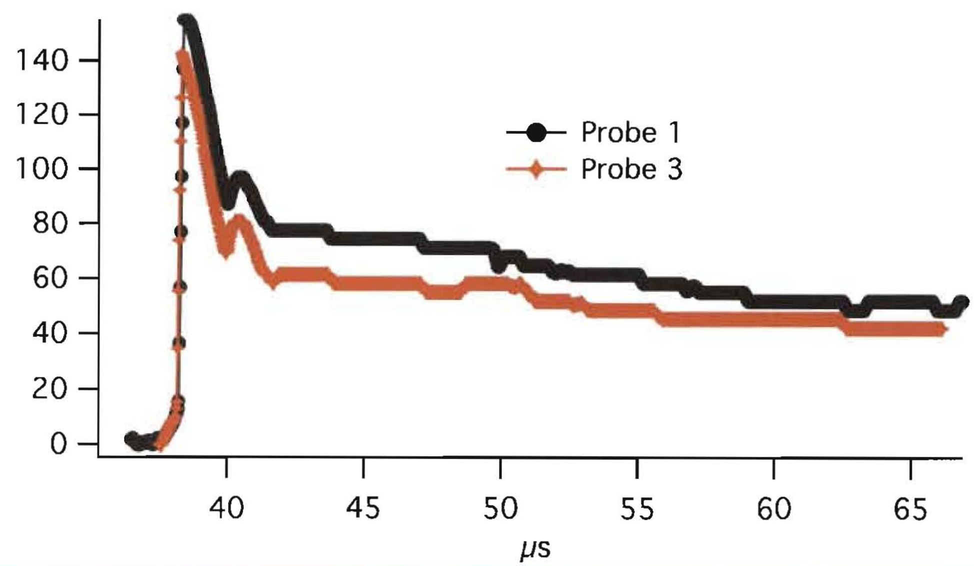
Cu Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam



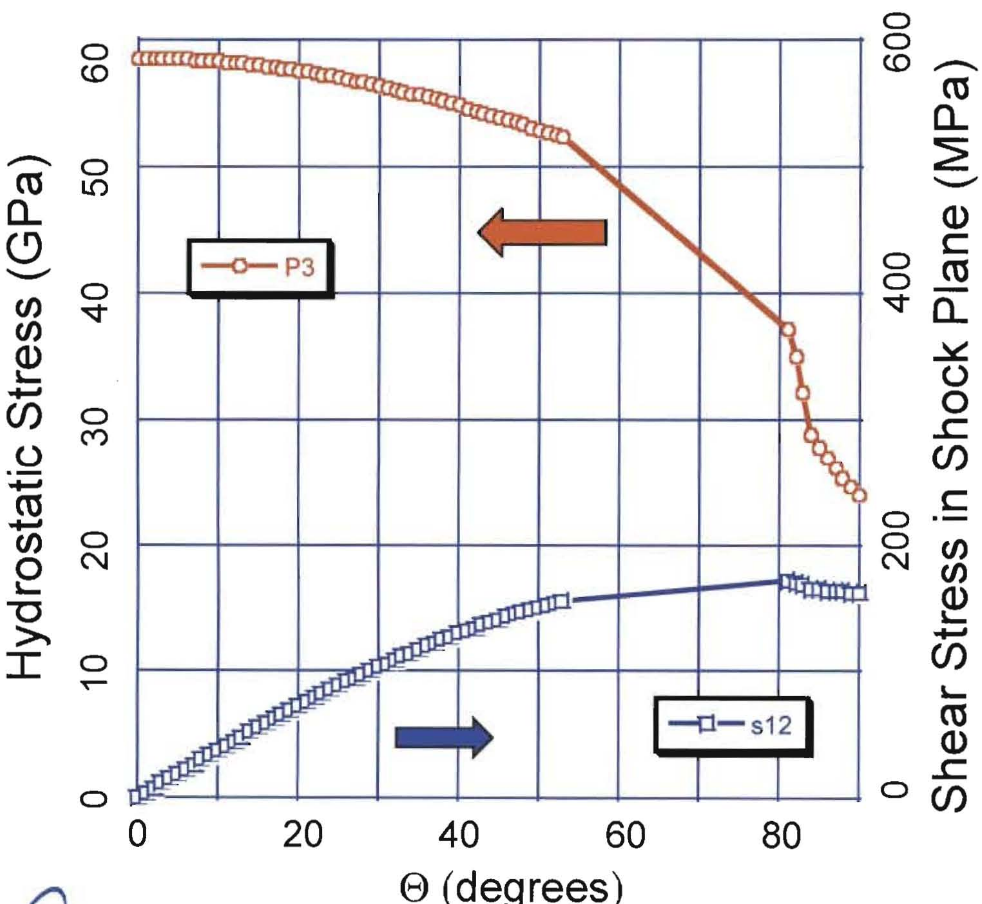
PDV DATA - Sweeping Detonation Drive: 4 mm Detasheet + 6.35mm Foam

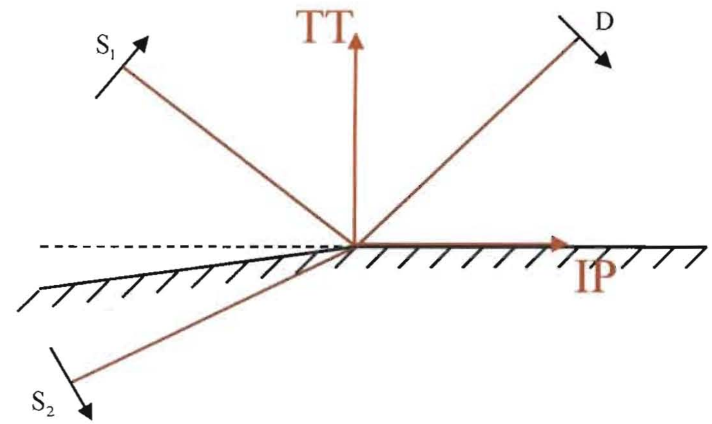






Tantalum – Spherical & Deviatoric Stress

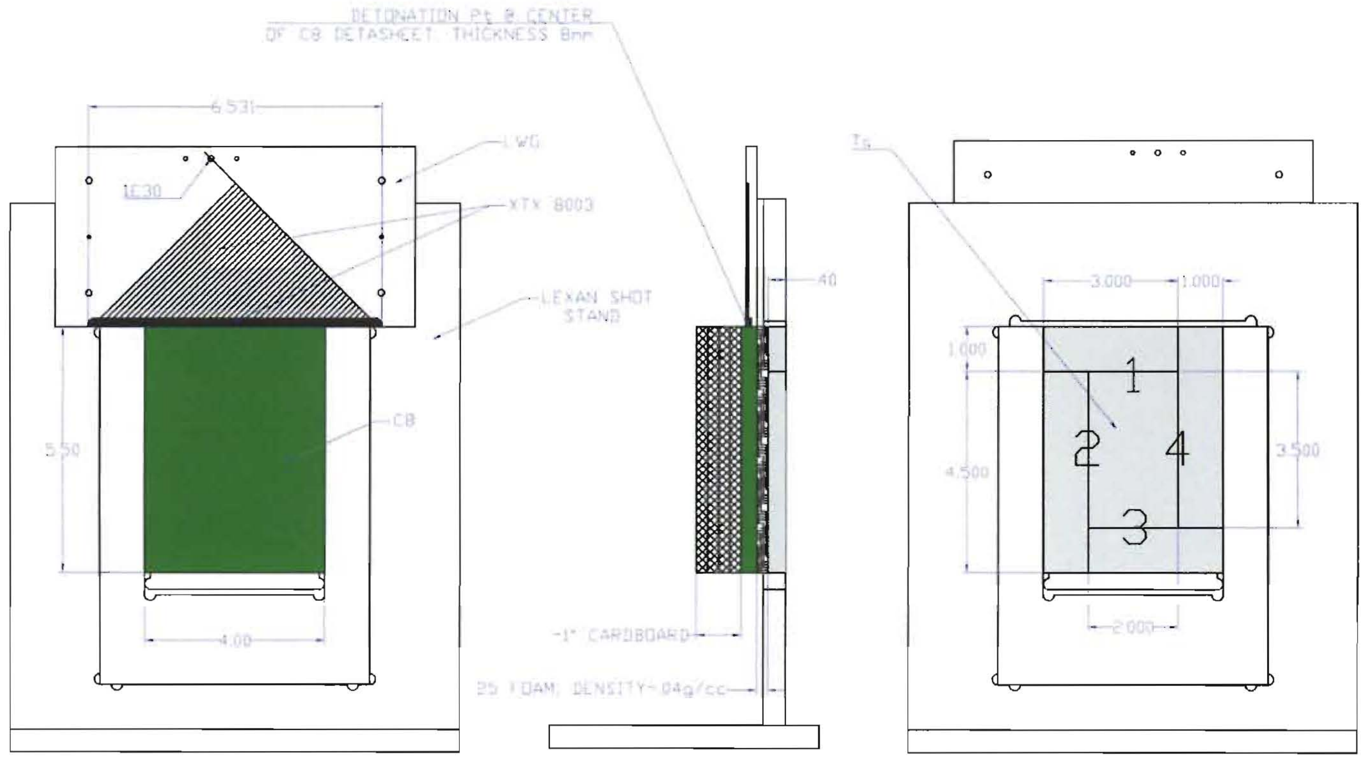




Two sources of shear possible:

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

1st Sweeping Spallation Experiment on Ta



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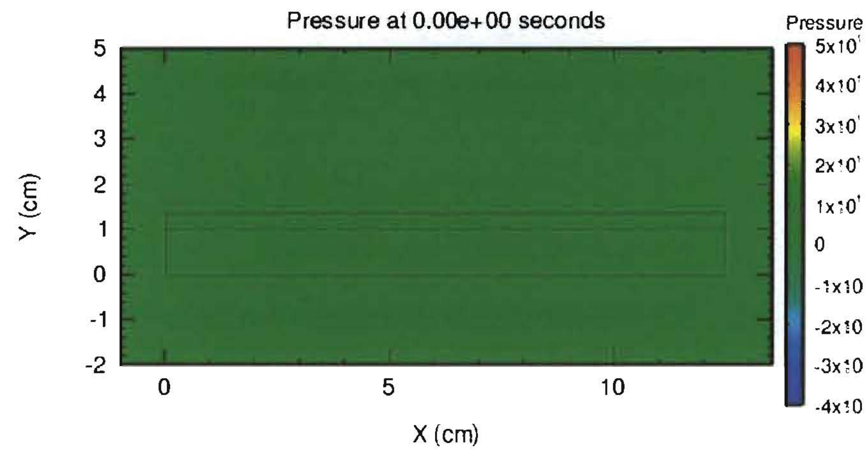
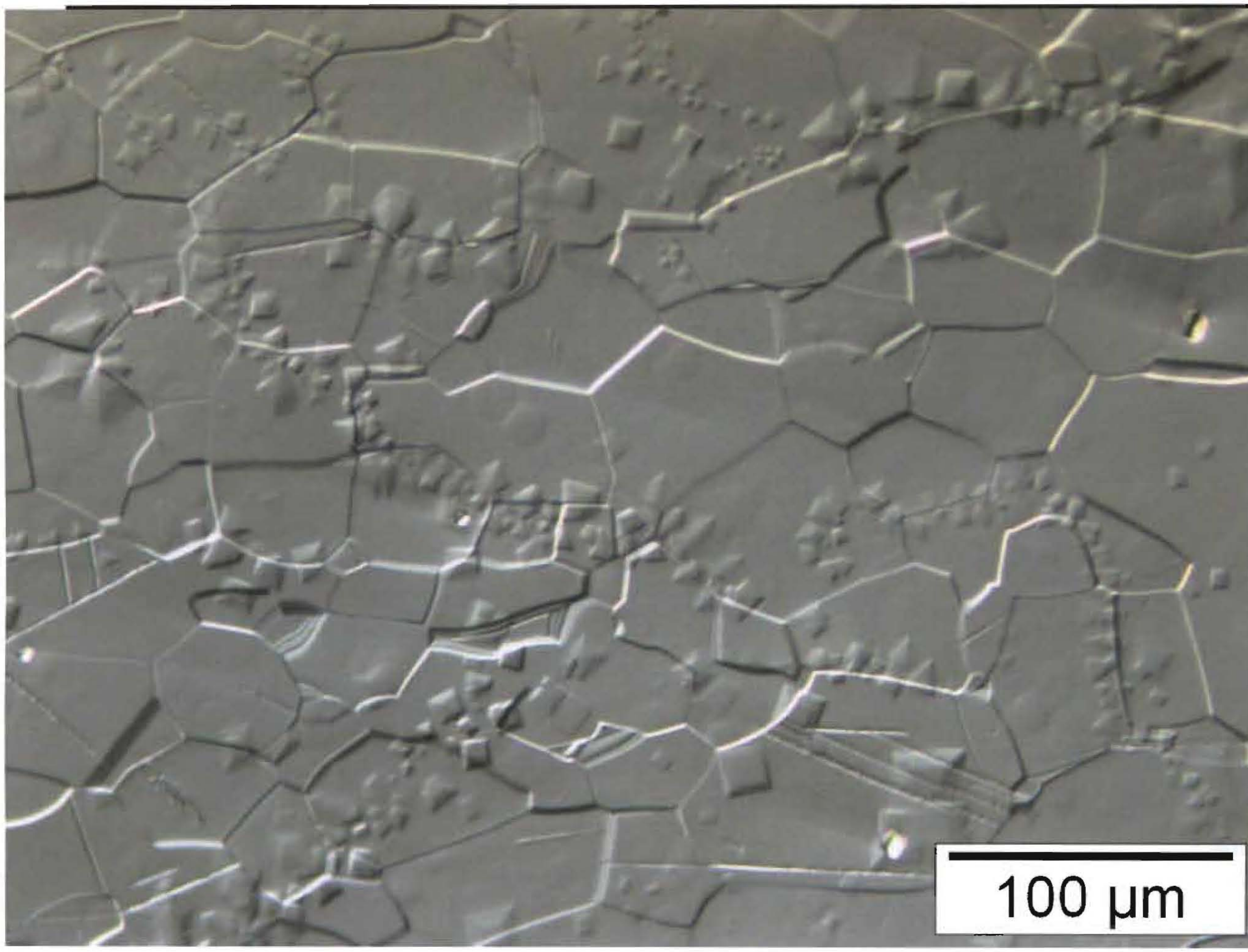
1st Sweeping Spallation Experiment on Ta

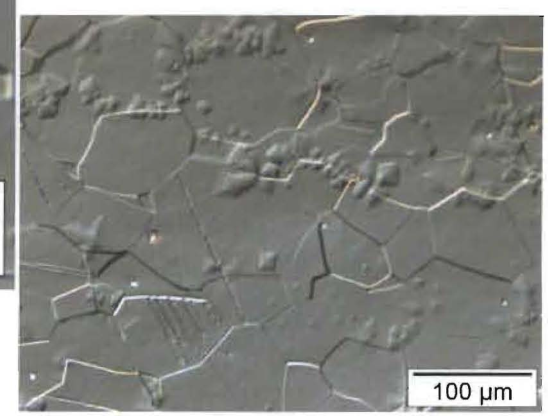


Preliminary CTH simulation of this experiment predicts spall layers formed : this is NOT seen experimentally.

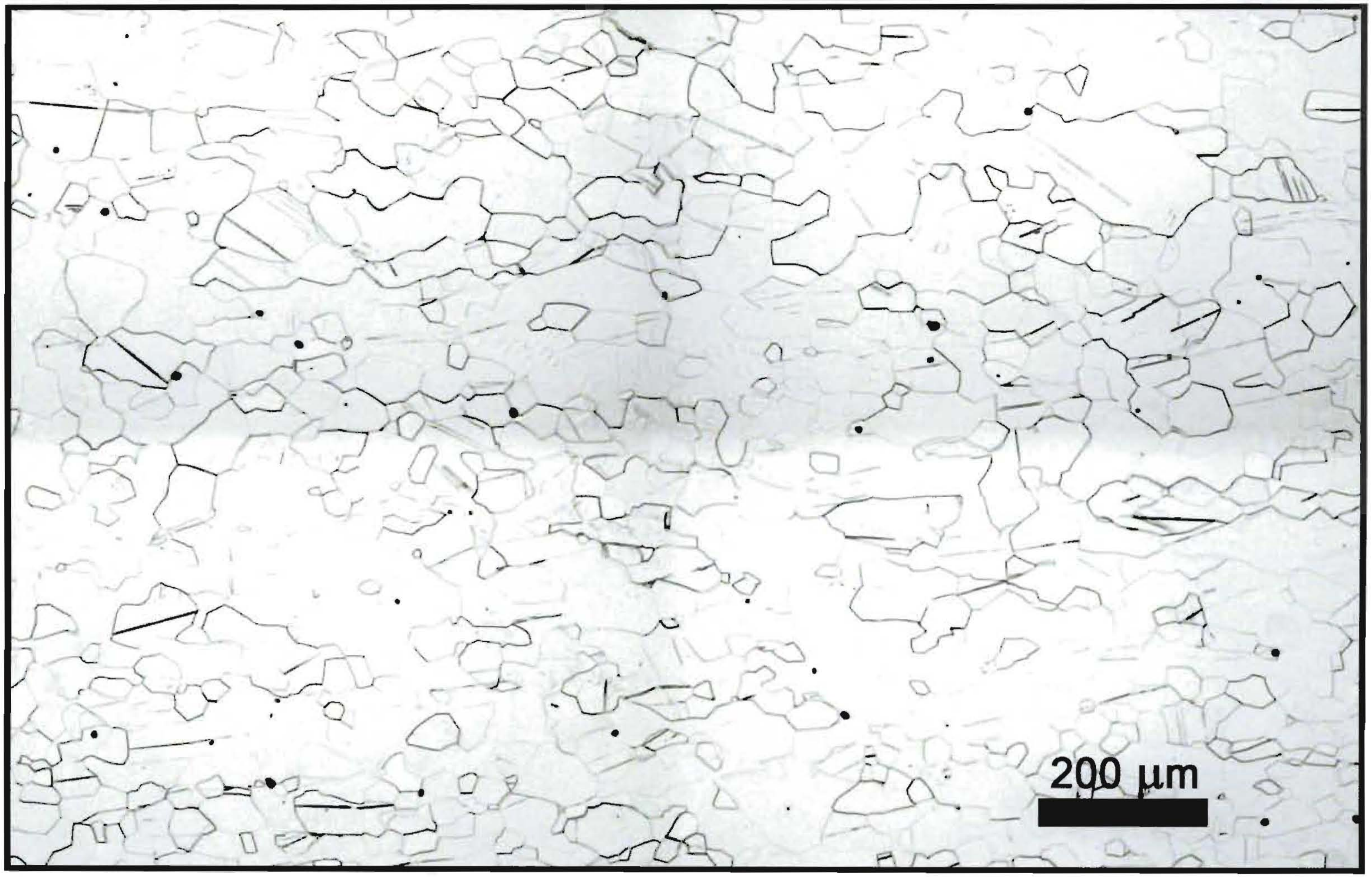
1st Sweeping Spallation Experiment on Ta



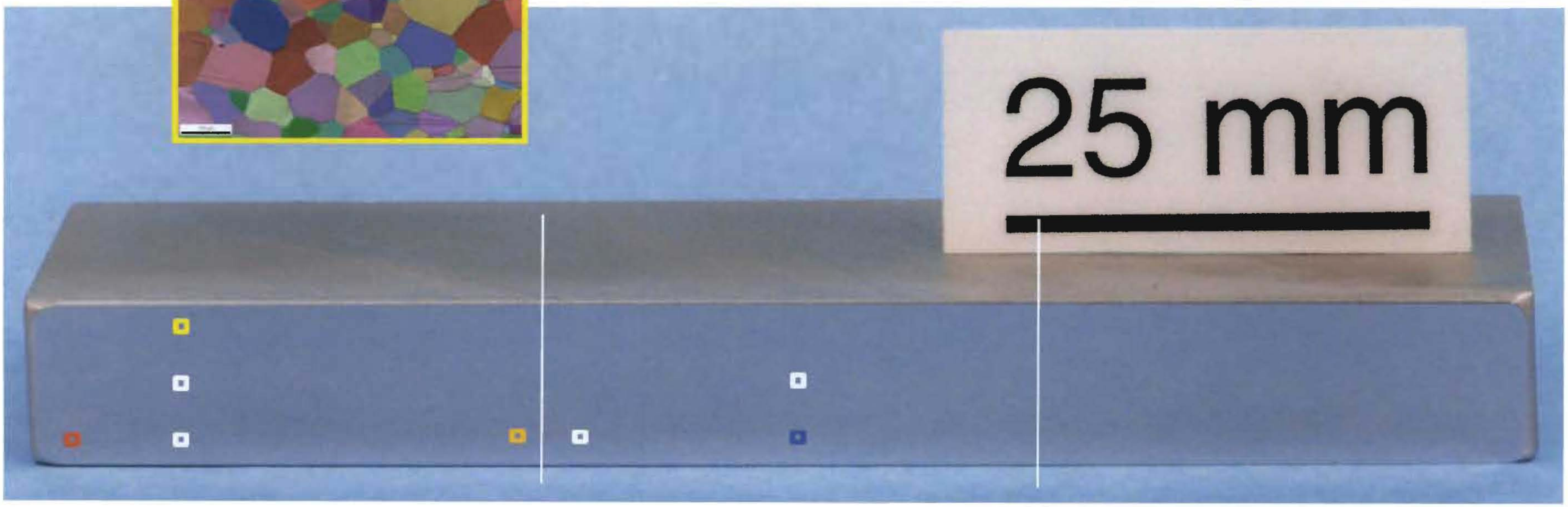
Optical metallography reveals slip-line surface offsets on the polished and etched plane section. Dislocation slip lines are seen concentrated along grain boundaries. Deformation twins are also seen.

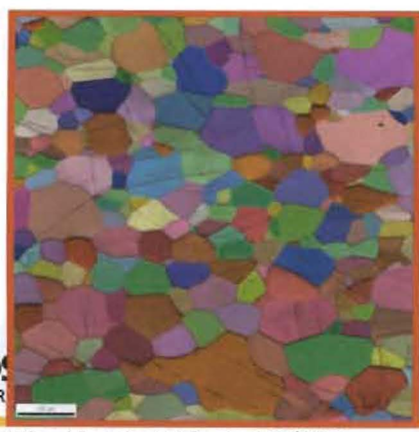


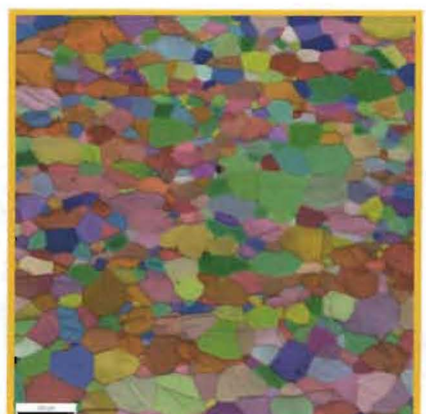
• Optical microscopy – indicates presence of voids and twins.
• Voids are small and 65-70% of them seem intragranular (some related to twin boundaries)

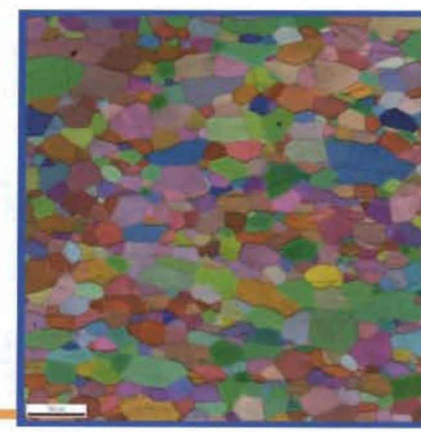


- Little squares indicate locations for EBSD
- No visible misorientations associated to voids
- Fine twins, more of them closer to the bottom edge than the top edge

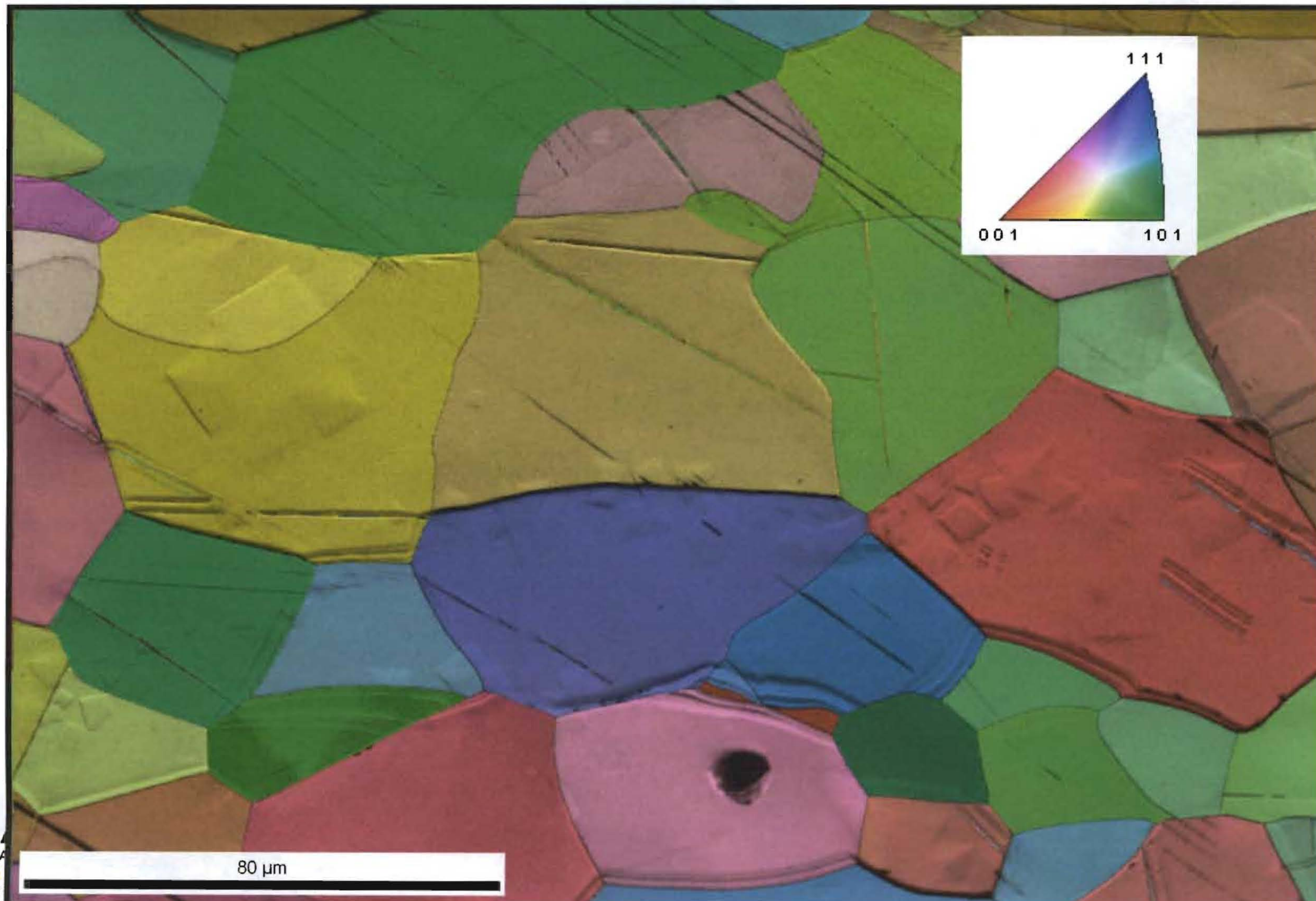








EBSD of dislocations - IPF map with IQ map superimposed



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.