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Title: Influence of Shockwave Obliquity on Deformation Twin Formation in Ta

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Influence of Shockwave Obliquity on Deformation Twin Formation in Ta

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Abstract. Energetic loading subjects a material to a "Taylor wave" (triangular wave) loading profile that experiences an evolving balance of hydrostatic (spherical) and deviatoric stresses. While much has been learned over the past five decades concerning the propensity of deformation twinning in samples shock-loaded using "square-topped" profiles as a function of peak stress, achieved most commonly via flyer plate loading, less is known concerning twinning propensity during non-1-dimensional sweeping detonation wave loading. Systematic small-scale energetically-driven shock loading experiments were conducted on Ta samples shock loaded with PETN that was edge detonated. Deformation twinning was quantified in post-mortem samples as a function of detonation geometry and radial position. In the edge detonated loading geometry examined in this paper, the average volume fraction of deformation twins was observed to drastically increase with increasing shock obliquity. The results of this study are discussed in light of the formation mechanisms of deformation twins, previous literature studies of twinning in shocked materials, and modeling of the effects of shock obliquity on the evolution of the stress tensor during shock loading.

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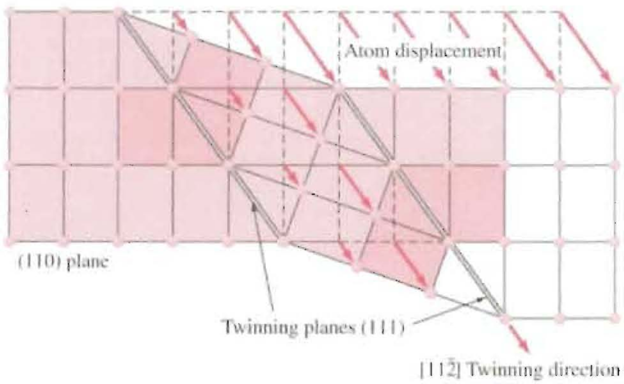
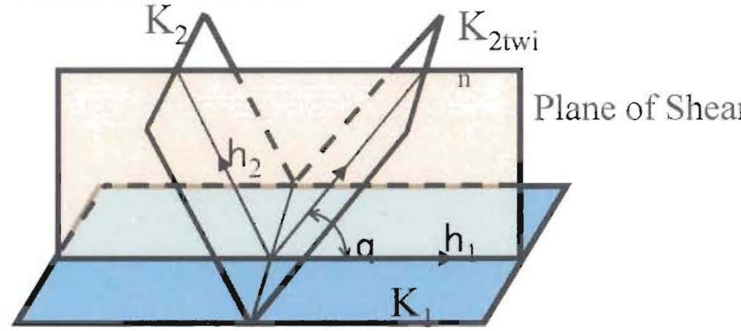
Deformation Twinning

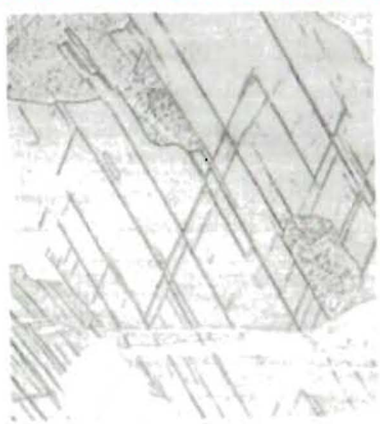
Twin initiation or growth occurs when the externally applied shear stress across the K_1 plane, resolved in the η_1 direction, reaches a "critical" value.





K_1, h_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.**



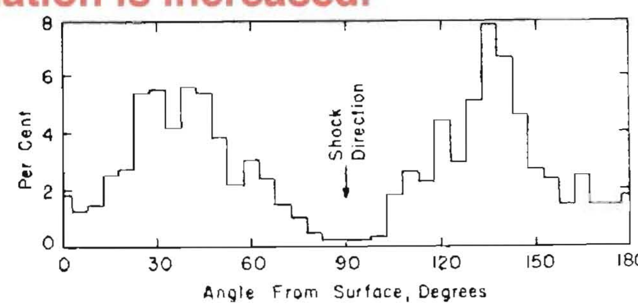


Fig. 14--Angular frequencies of markings on brass after 550-kbar normal shock. Plane of section includes shock direction.

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

Twinning during shock loading: A complex series of differing observations

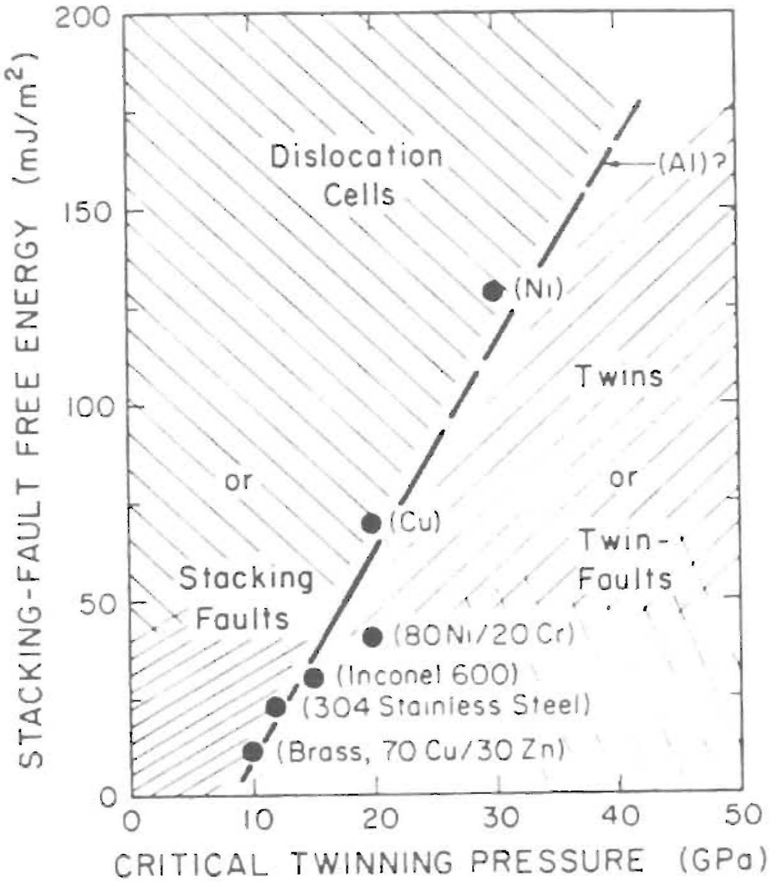


FIG. 1.15: *Stacking-fault free energy versus critical twinning pressure (for initial twinning in [001] directions) for a number of FCC metals and alloys where the residual strains were very small or negligible ($<1\%$), and $\Delta t = 2\mu s$, i.e. the shock pulse duration shown in Fig. 1.7 was constant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

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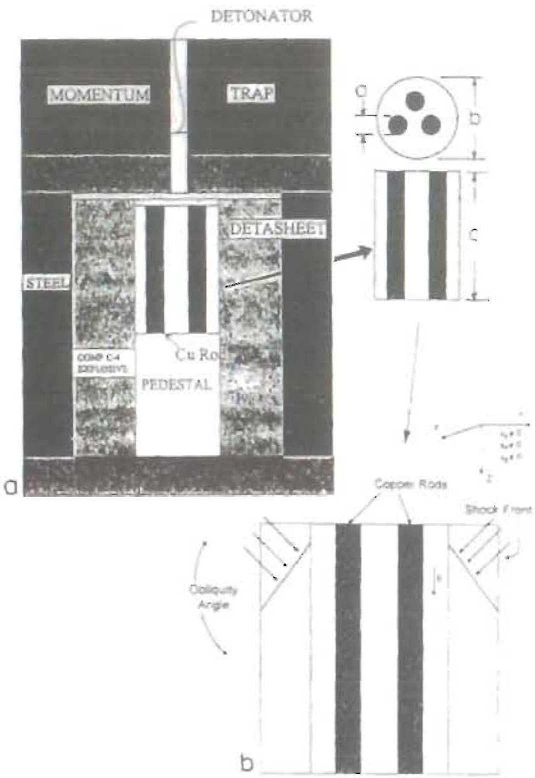
Twinning during shock loading: A complex series of differing observations in Cu & Ta observations



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."

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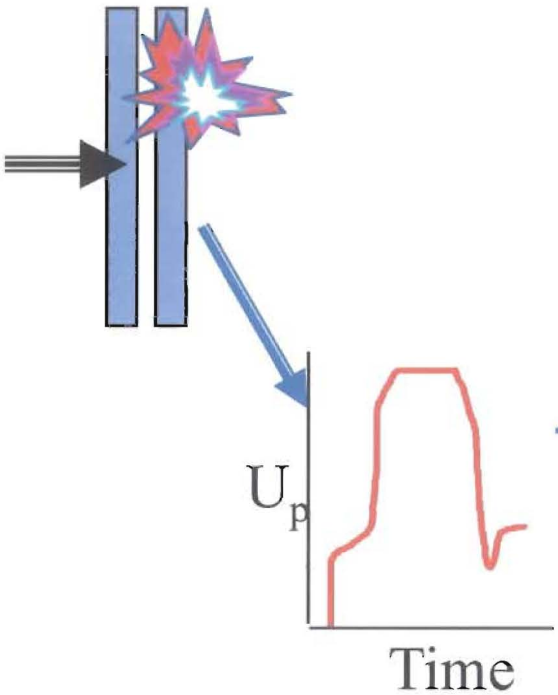
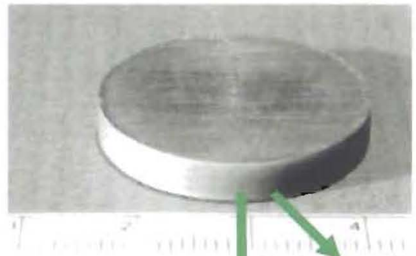
Investigation of shock loading: a question of time

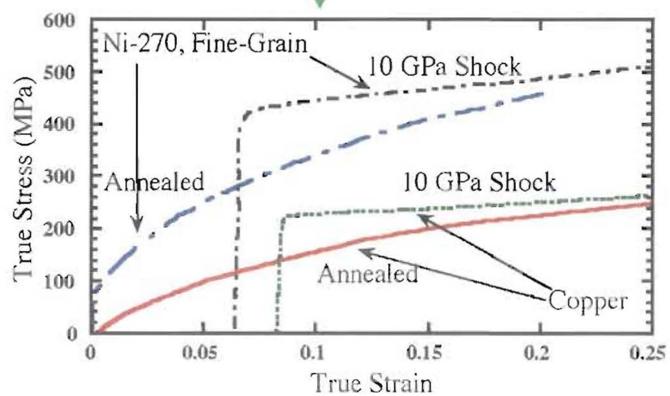


Wave Profile

+ ***Characterization***

Shock Recovery





→ Predictive

Physically
-Based
Modeling

$[illegible] = b\,[illegible]_m v$

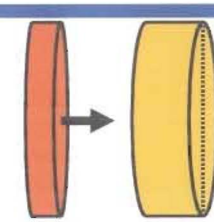
0

TIME ⟹

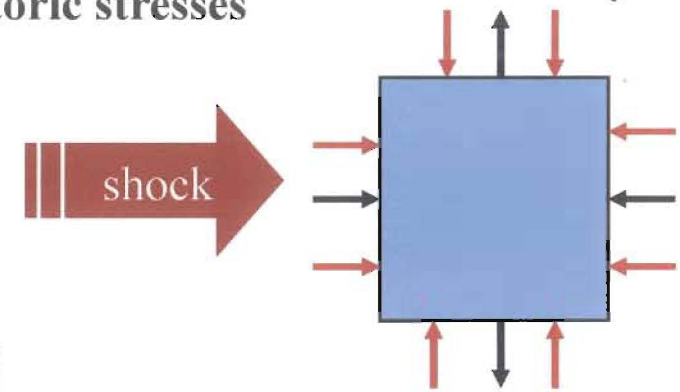
Strong Shock Loading

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

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



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

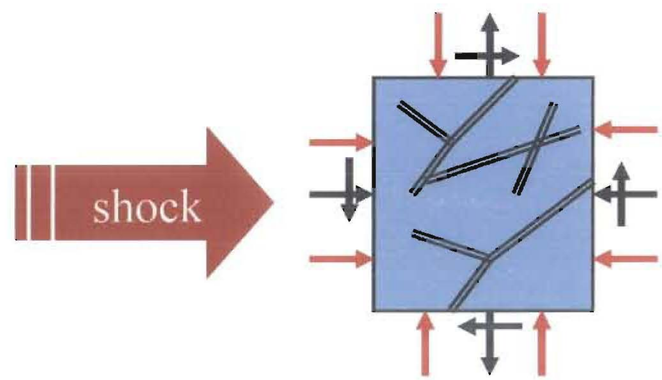


Uniform/Stable Deformation

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

Deviatoric
Spherical

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



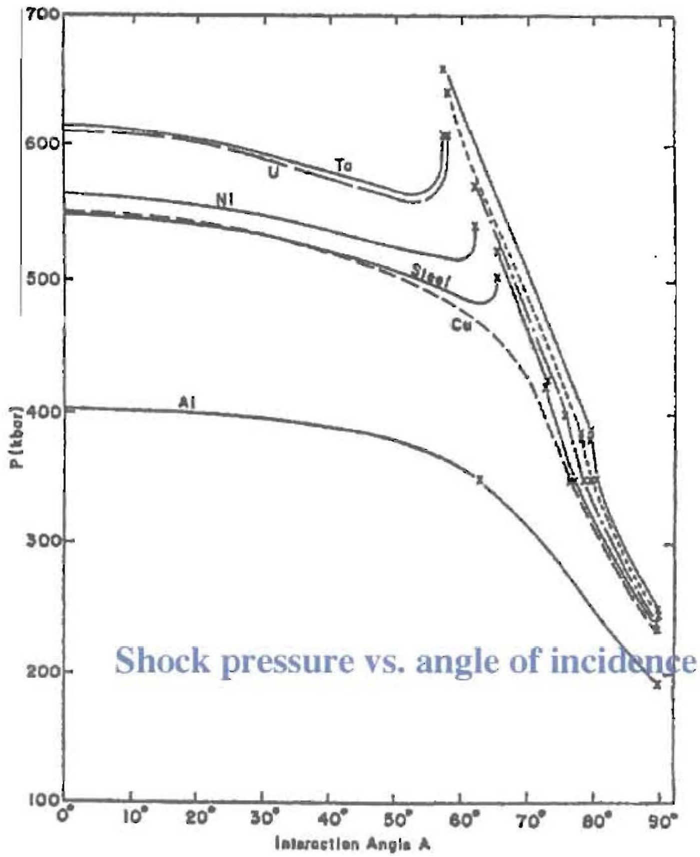
Unstable Deformation with significant shear

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

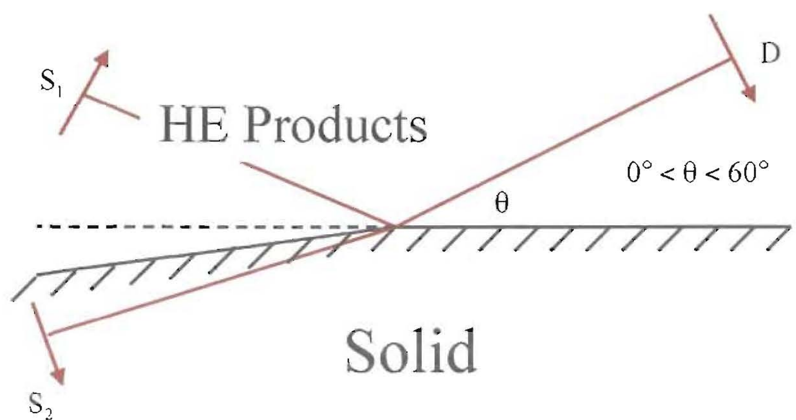


Shock pressure vs. angle of incidence

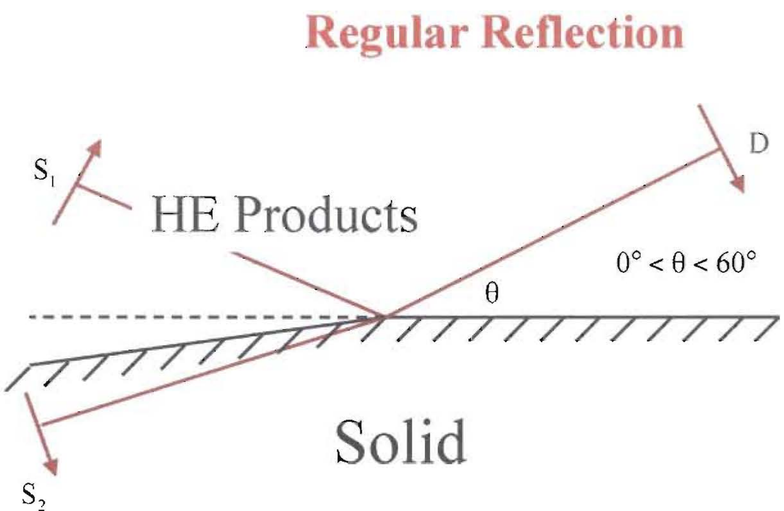
J.W. Walsh
LA-9612-MS

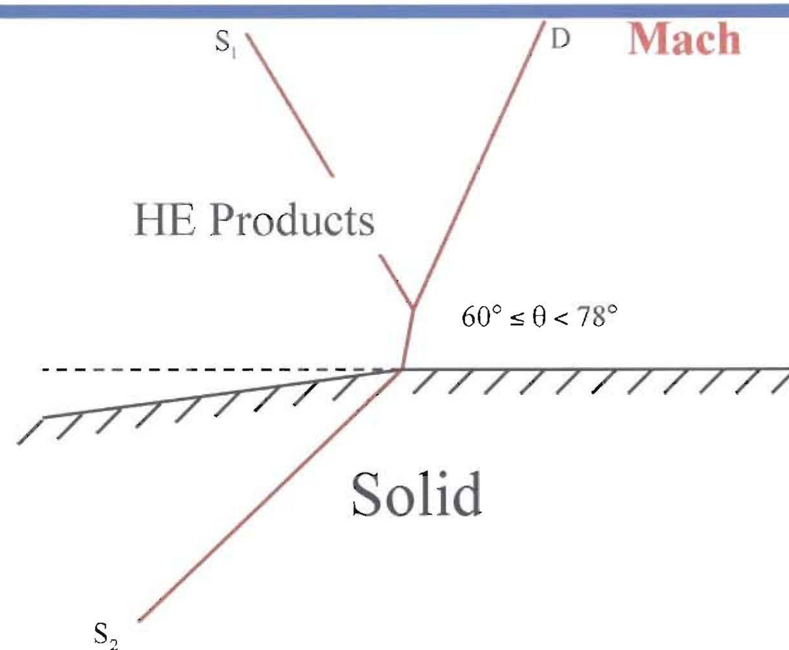
Four Regimes Possible:

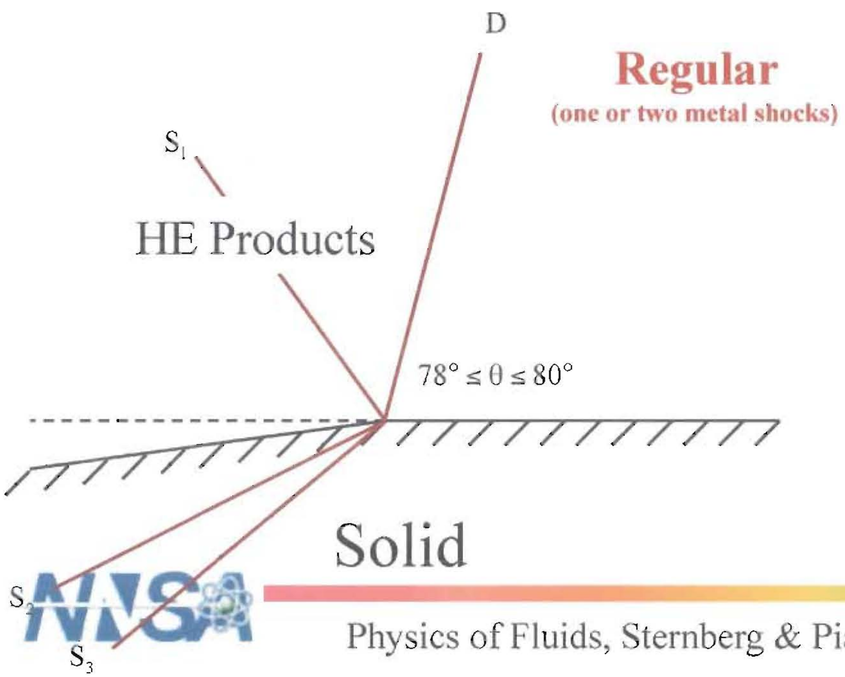
1. ***Regular reflection (0 – 58 degrees)***
2. **Mach reflection (58 – 78 degrees)**
3. **Regular with multiple metal shocks (78- 79)**
4. **Regular with product rarefaction (79 - 90)**

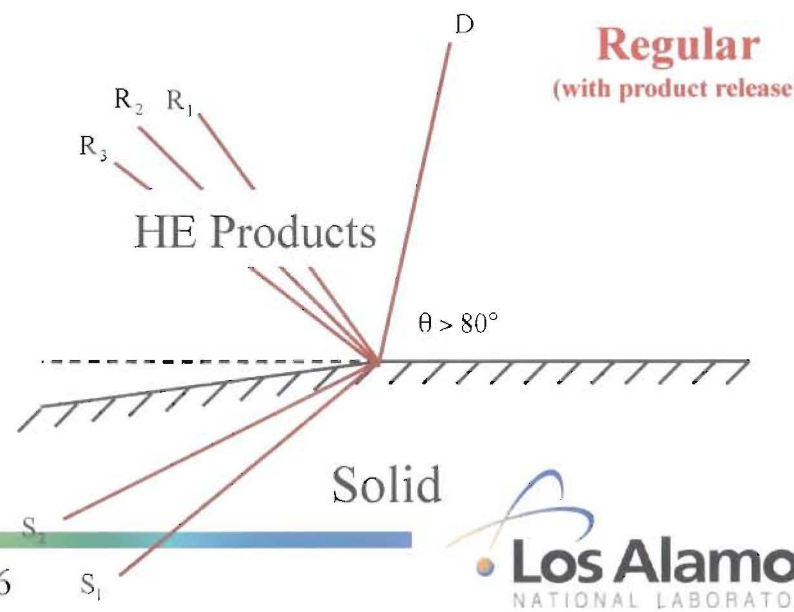


Oblique Reflection Wave Structures



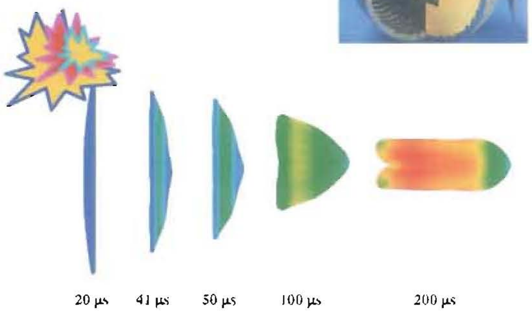






Physics of Fluids, Sternberg & Piacesi, 1966

Effect of HE-Shock Driven Shock Prestraining on Materials

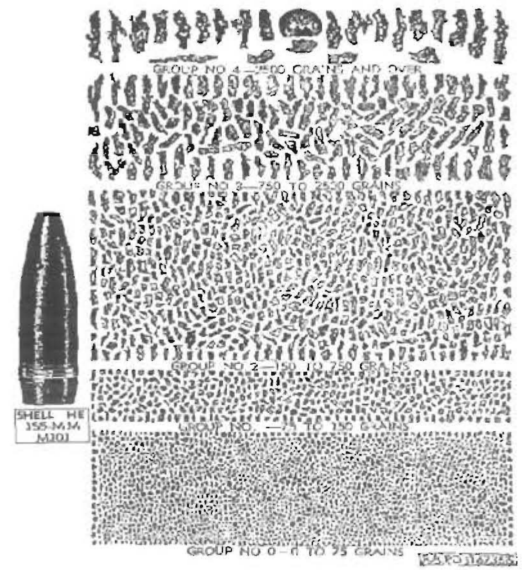


Liners / warheads

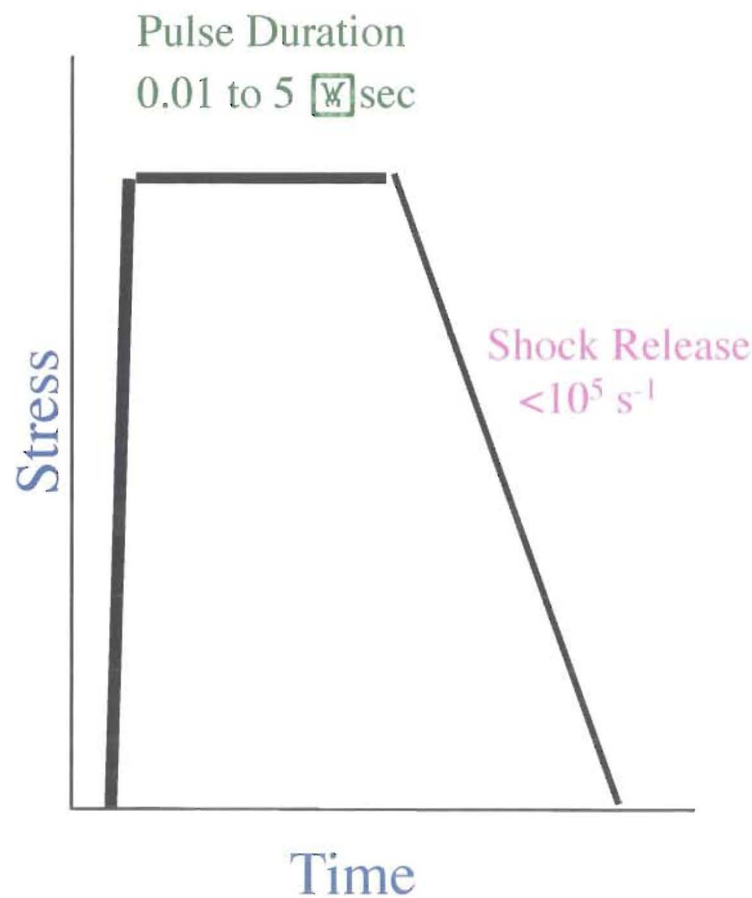
Constitutive Response of Warheads / weapon materials are **preconditioned** by HE preshock load cycle.

↓

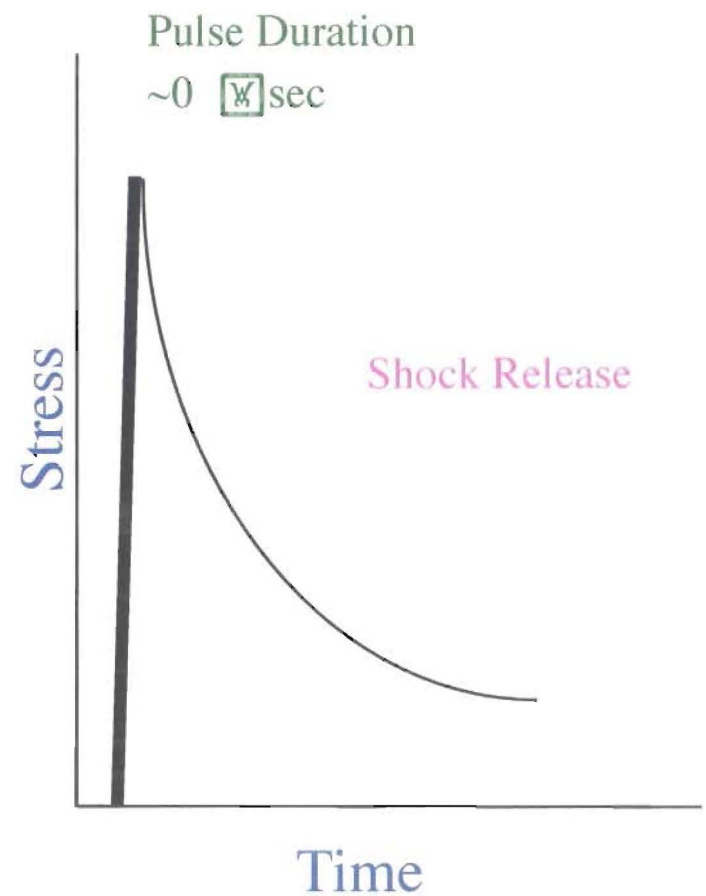
Predictive Performance of Warhead **requires** knowledge of shock hardening



Shock-Wave Prestrain - Flyer Plate vs. Taylor Wave



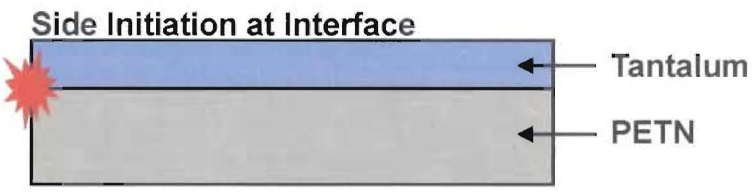
Flyer-Plate

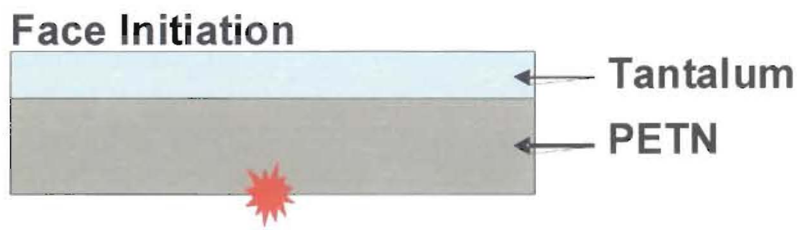


HE-Taylor Wave

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:*

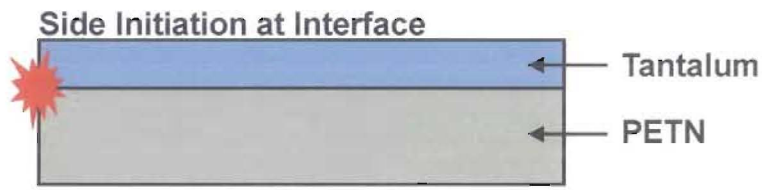




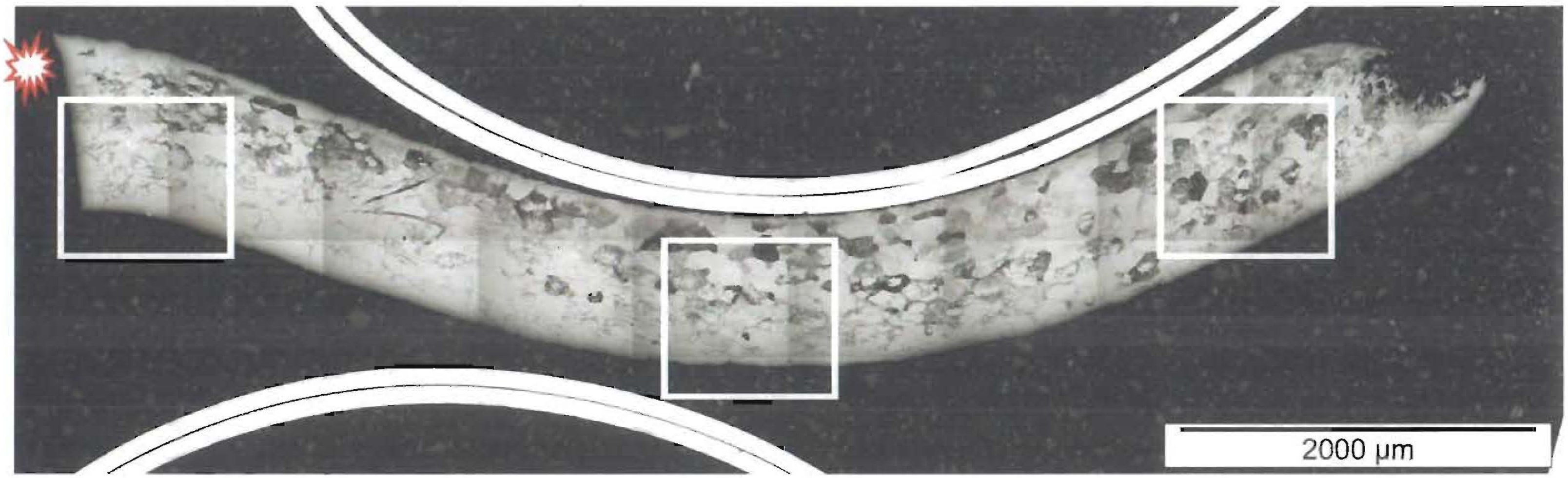
EBSD analysis:

- *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)



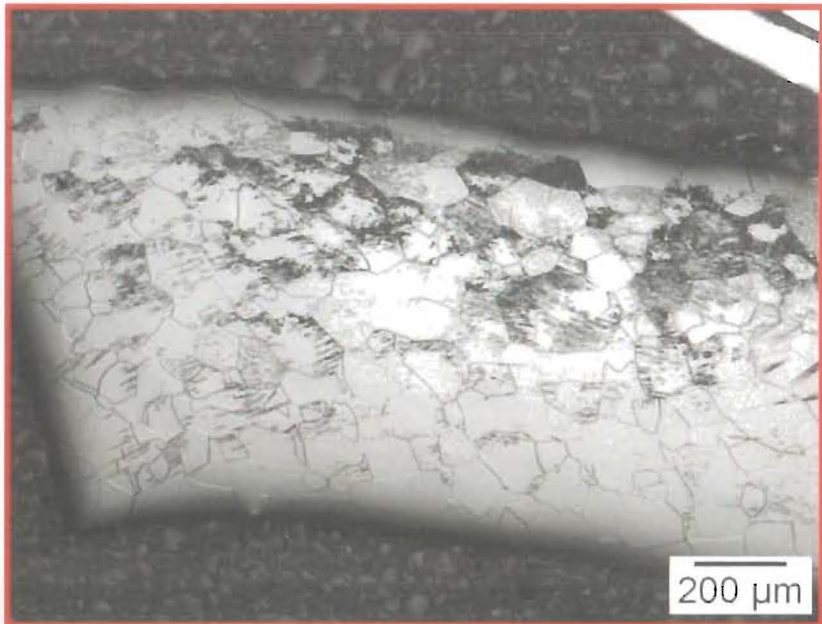
Optical image @100x



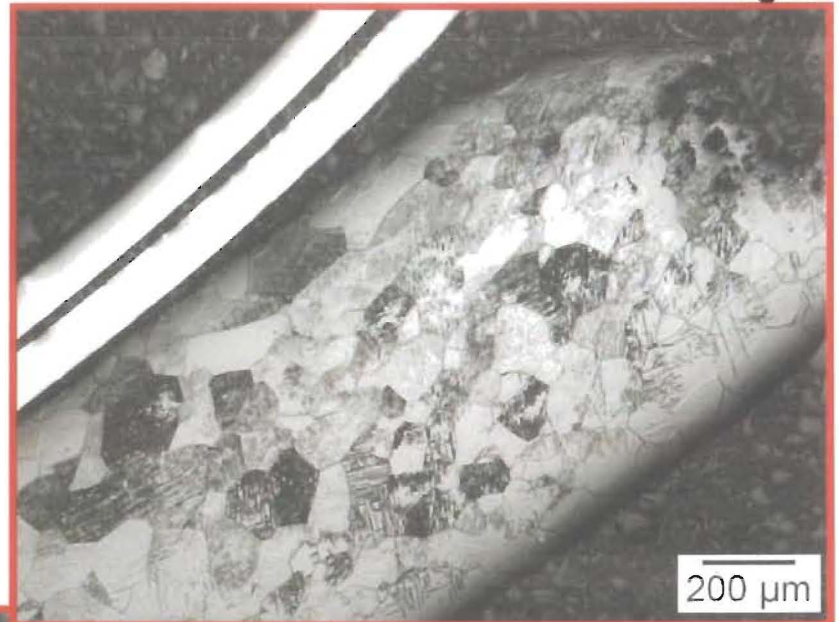
- Qualitatively, the amount of twinning increases from left to right, with a visibly higher concentration along the upper edge. (adjacent to HE)
- Red rectangles and twin close-up images are shown at larger scale on the next slide.

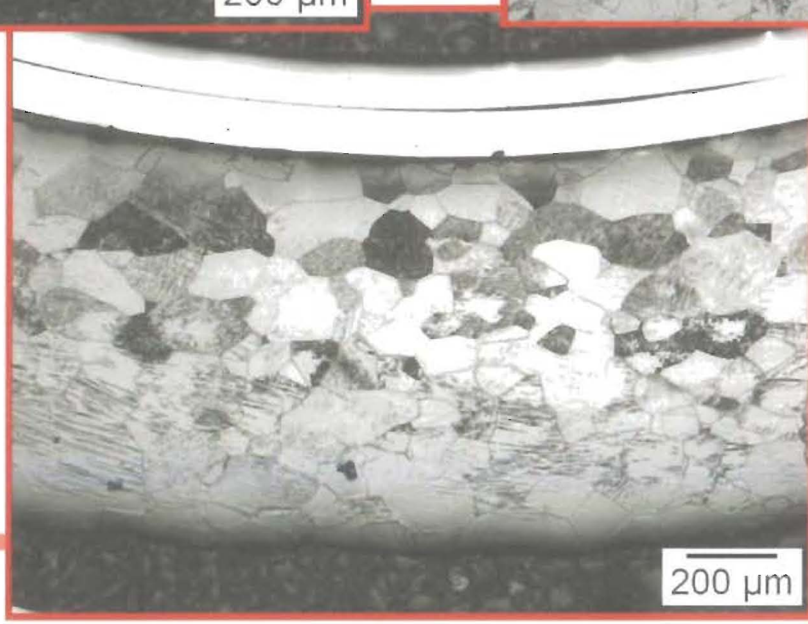
UPSET-FORGED Ta Specimen (UF-13)- *Optical Images*

Left



Right





Center

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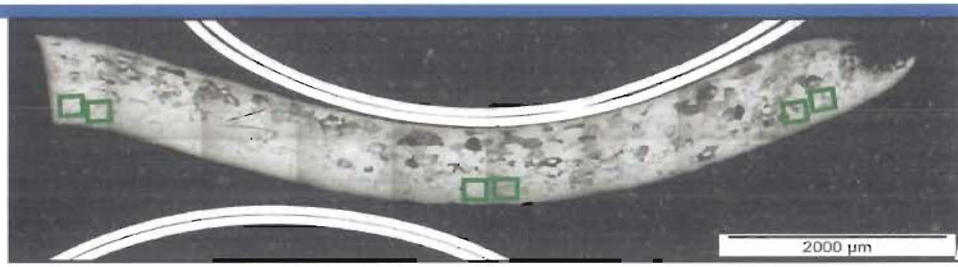
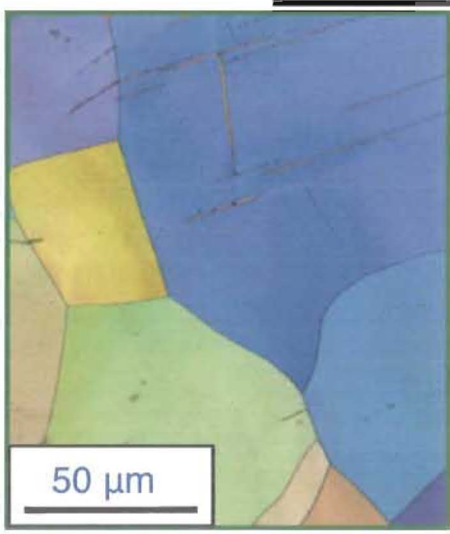
50 µm

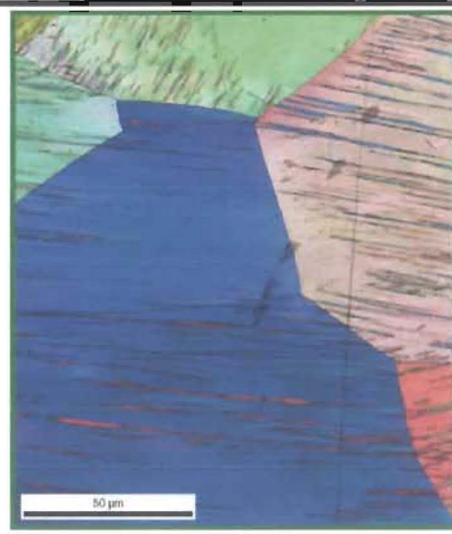
UPSET-FORGED Ta Specimen (UF-13)- *EBSD data*

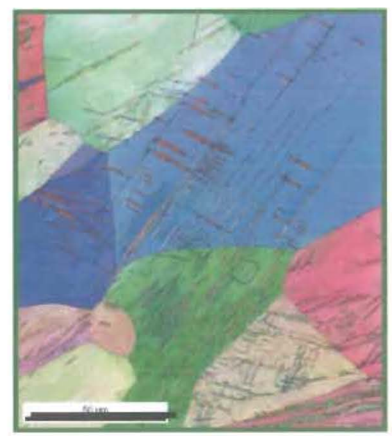


50 µm

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

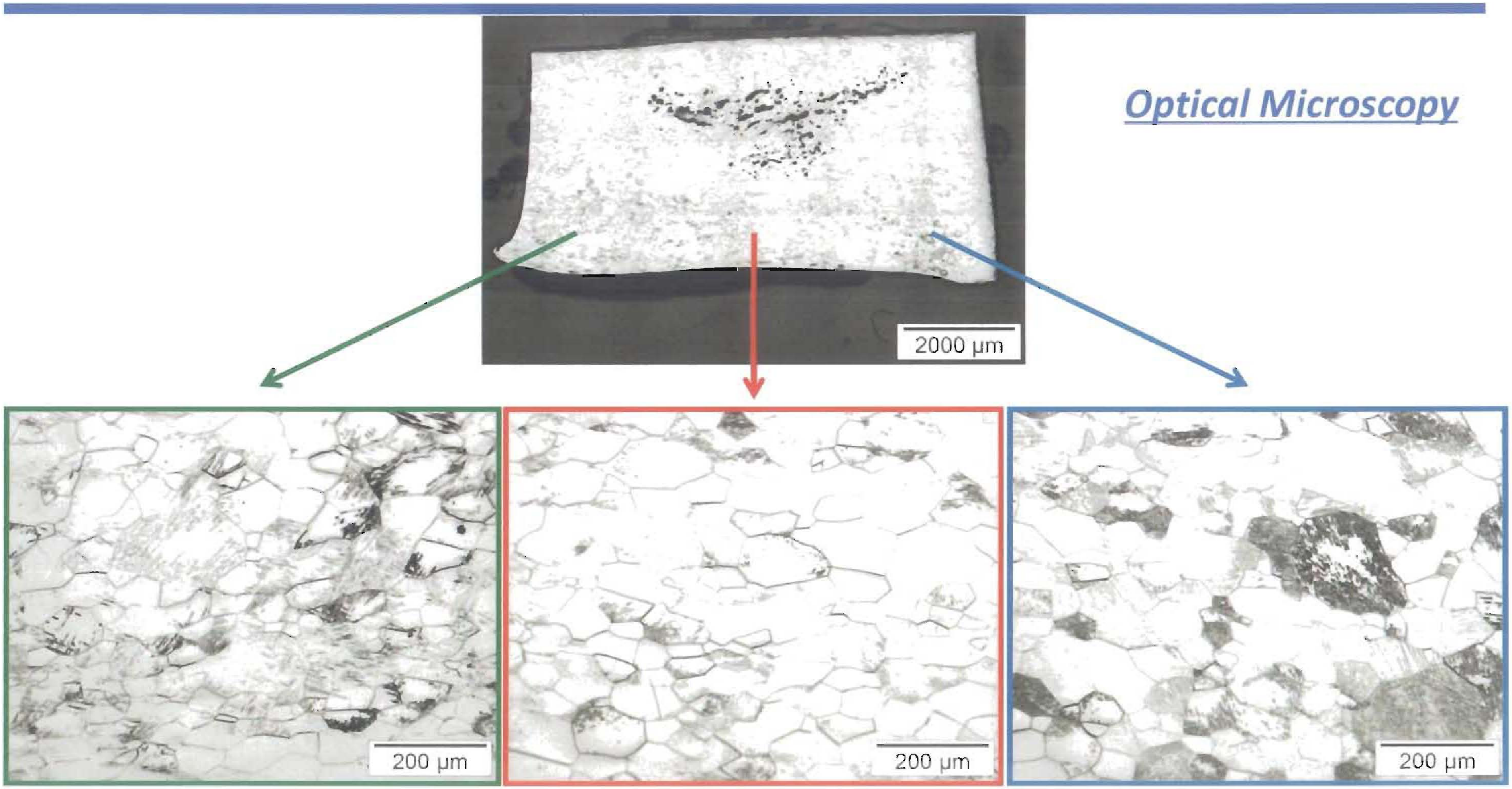






- Visually there are more twins in the center and right regions compared to the left region; EBSD confirms these observations

Center-Detonated Ta sample



Optical Microscopy

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

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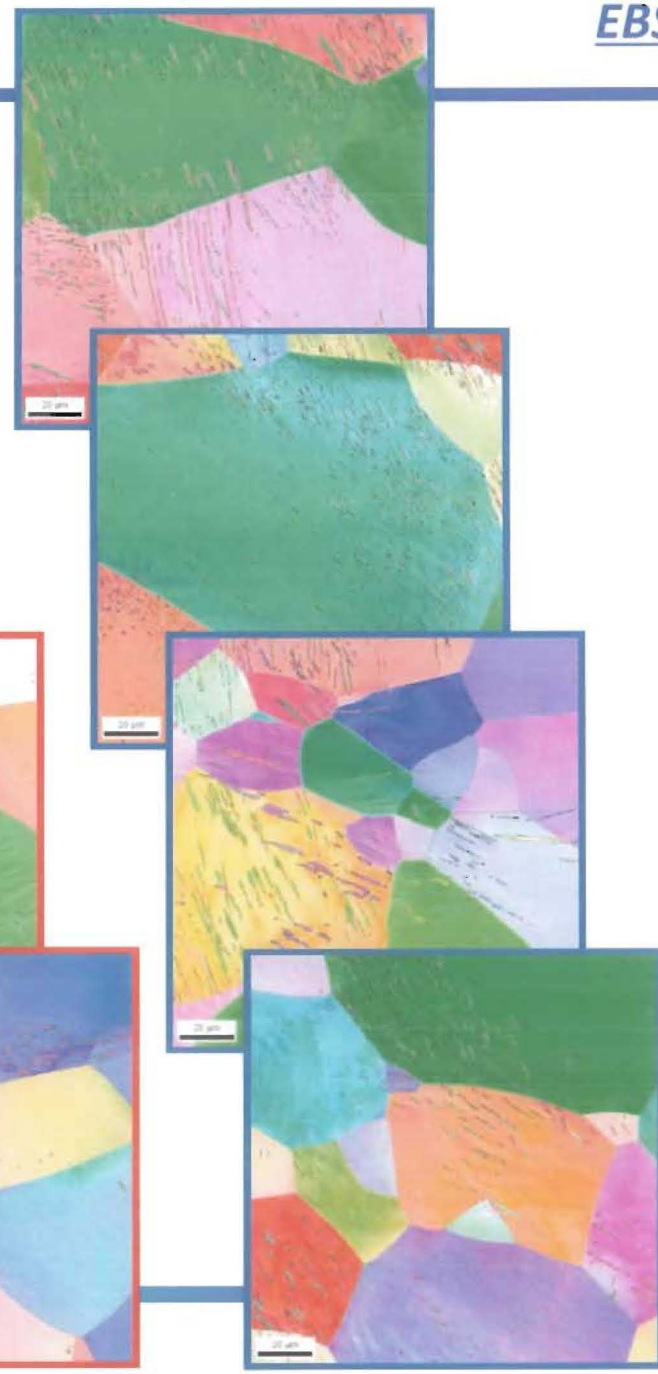
EBSD

Left Bottom

Center Bottom

Right Bottom



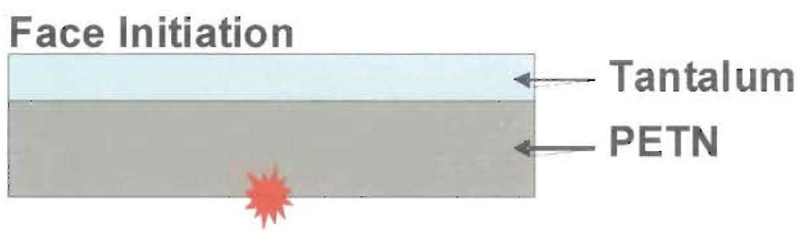
1 1 1

0 0 1 1 0 1

Center-Detonated Ta sample

Summary table

Location	Left Bottom	Center Bottom	Right Bottom
Average Twin Fraction	0.172	0.059	0.167
Average Twin Boundary Fraction	0.406	0.128	0.649

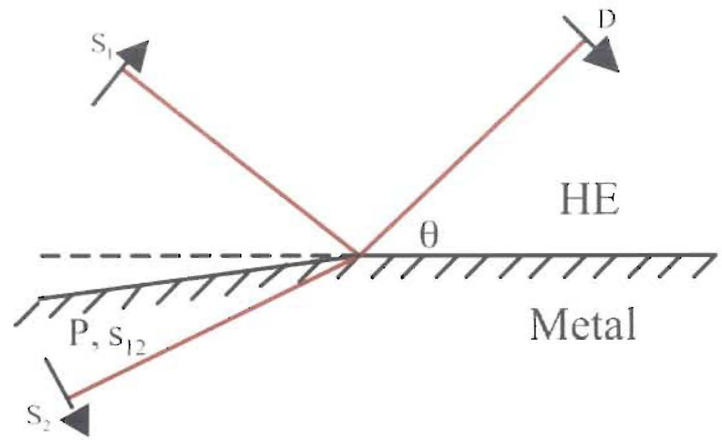


Modeling of Oblique Shock Loading of Ta

- 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.



For Solids: Oblique Shock Equations

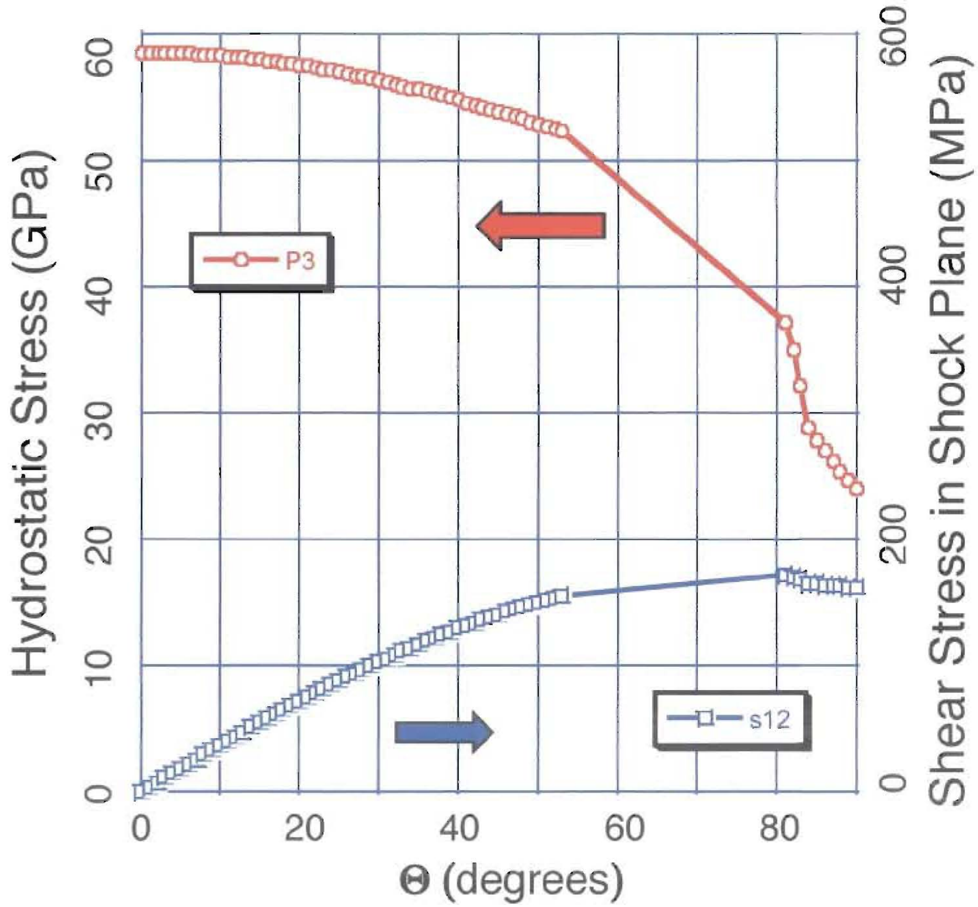
- **Continuity Jump:** $\left\lfloor \rho\left(\underline{q}\cdot\underline{m}\right)\right\rfloor = 0$ where $\underline{q} = -D/\sin\theta\,\hat{e}_1 + \underline{u}$
- **Momentum Jump ($\underline{m}$):** $\left\lfloor \left(\underline{\underline{\sigma}}\cdot\underline{m}\right) - \underline{q}\,\rho\left(\underline{q}\cdot\underline{m}\right)\right\rfloor \underline{m} = 0$
- **Momentum Jump ($\underline{s}$):** $\left\lfloor \left(\underline{\underline{\sigma}}\cdot\underline{m}\right) - \underline{q}\,\rho\left(\underline{q}\cdot\underline{m}\right)\right\rfloor \underline{s} = 0$
- **1st Law Jump:** $\rho\left(\underline{q}\cdot\underline{m}\right)\left[e + 1/2\,\underline{u}\cdot\underline{u}\right] + \left\lfloor \underline{u}\cdot\underline{\underline{\sigma}}\right\rfloor \underline{m} = 0$
- **Constitutive Form:** $\underline{\underline{\sigma}} = \underline{\underline{\sigma}}\left(\underline{\underline{\varepsilon}}, e, \text{other IVs}\ldots\right)$
- **Alternate Constitutive Form:** $\left\lfloor \underline{\underline{\sigma}}\right\rfloor = \mathbf{T} : \left\lfloor \underline{\underline{\varepsilon}}\right\rfloor$
- **Strain Jump:** $\left[\underline{\underline{\varepsilon}}\right] = \dfrac{1}{\rho\left(\underline{q}\cdot\underline{m}\right)^2}\left[\underline{\underline{\sigma}}\right]$

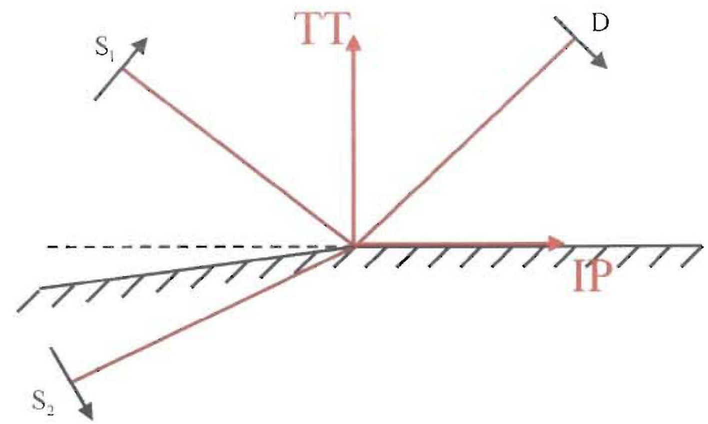
$$\left\{\underline{m}\cdot\mathbf{T}\cdot\underline{m} - \rho\left(\underline{q}\cdot\underline{m}\right)^2\underline{\underline{I}}\right\}\left[\underline{m}\cdot\underline{\underline{\sigma}}\right] = \underline{0}$$

Bottom Line: 11 Eqns & 12 Unknowns: $\underline{\underline{\sigma}}, \rho, D, \underline{u}, e$

Very nonlinear equation set!

Tantalum – Spherical & Deviatoric Stress





Two sources of shear possible:

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

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

- 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.

- OIM 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.