# Dynamic Consolidation of Al 6061-T6 Powders

## A computational investigation

**August 7, 2009**

**D. Anthony Fredenburg[1,2], Naresh Thadhani[1], Tracy Vogler[3]**

**[1]Georgia Institute of Technology, Atlanta GA 30332**

**[2]Sandia National Laboratories, Albuquerque NM 87185**

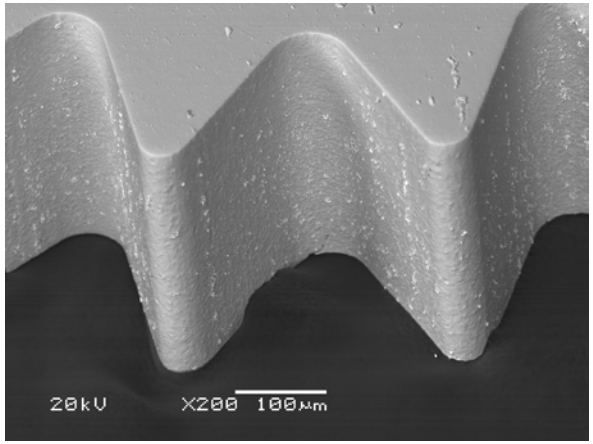
**[3]Sandia National Laboratories, Livermore CA 94550**

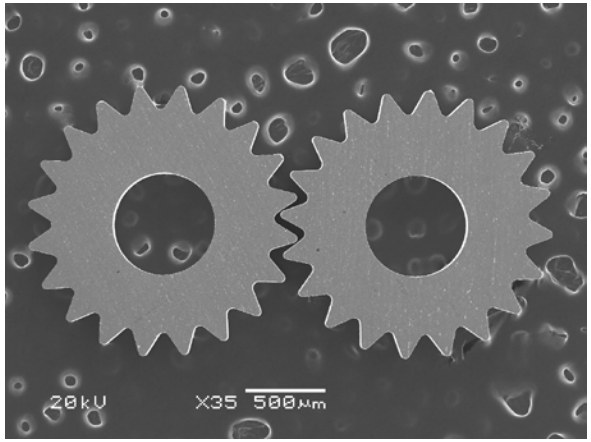
**SAND2009-5179P**

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Motivation

As component size is reduced to 100's of microns, grain size must be correspondingly reduced to ensure homogeneity.




*Can shockwave consolidation be used to consolidate nanocrystalline powders into bulk components without significant grain growth?*



Sandia National Laboratories

# Outline

## I. Material System

- Processing
- Microstructures

## II. Computational

- Initial configuration
- Results: $U_S$-$u_P$, P-V

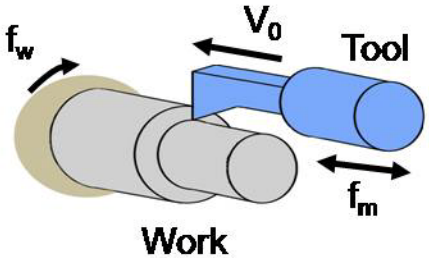
## III. Concluding Remarks

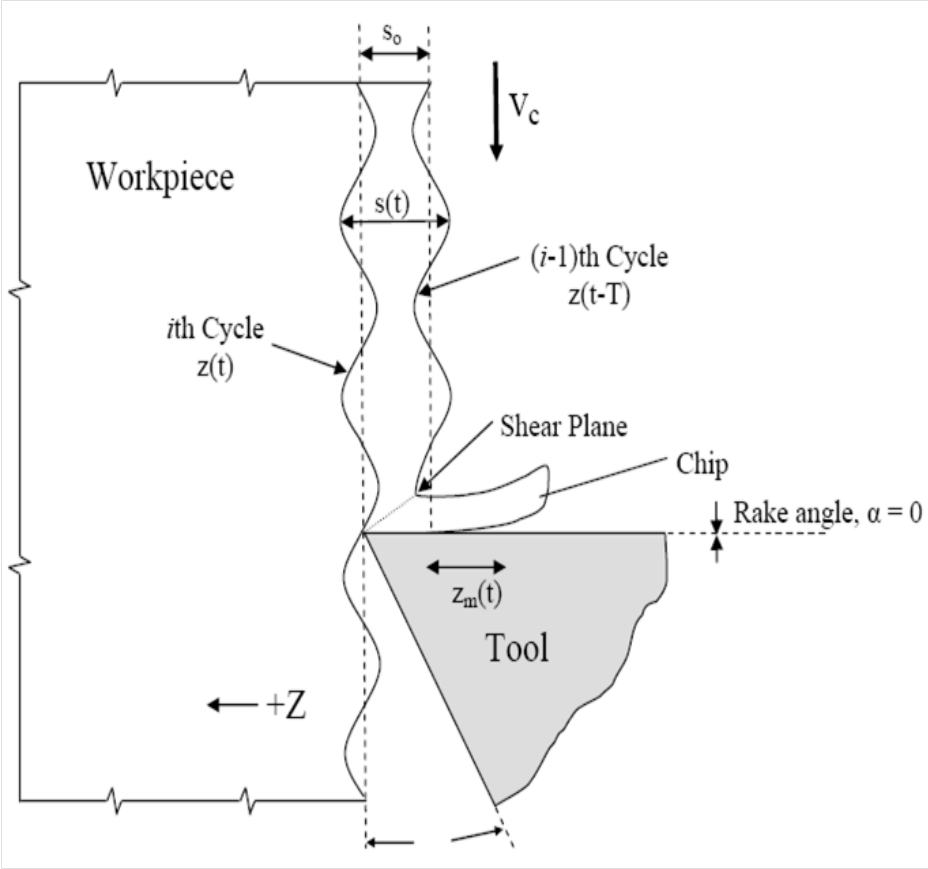


Sandia National Laboratories

# I. M4 Sciences Al 6061-T6

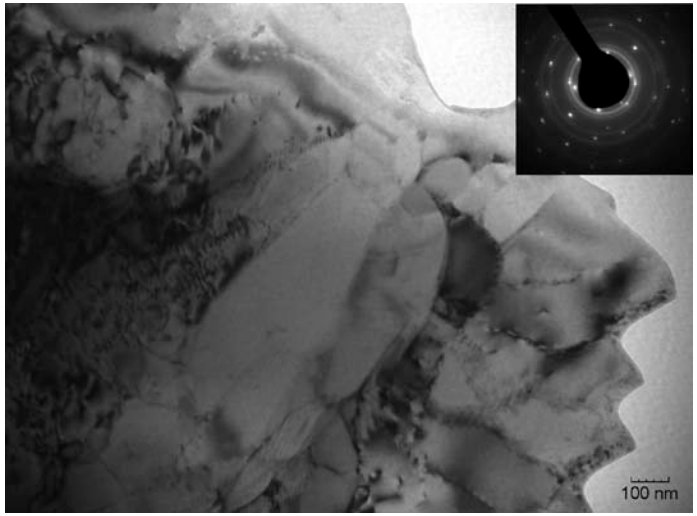
- **Formed through frequency modulation assisted machining**
- **Morphology and degree of nanocrystallinity**
  - **Rotational velocity**
  - **cutting (rake) angle**
  - **Frequency of modulation**



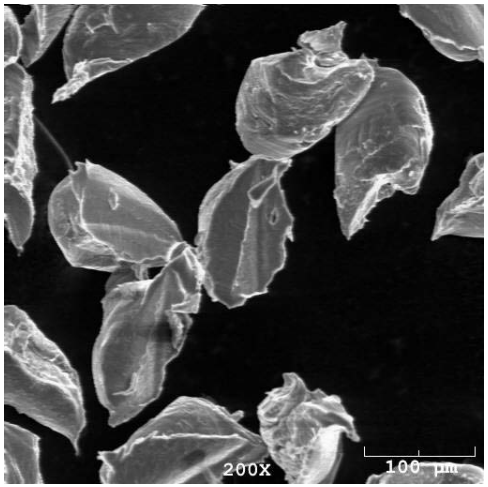

*C.J.Saldana (2006)*

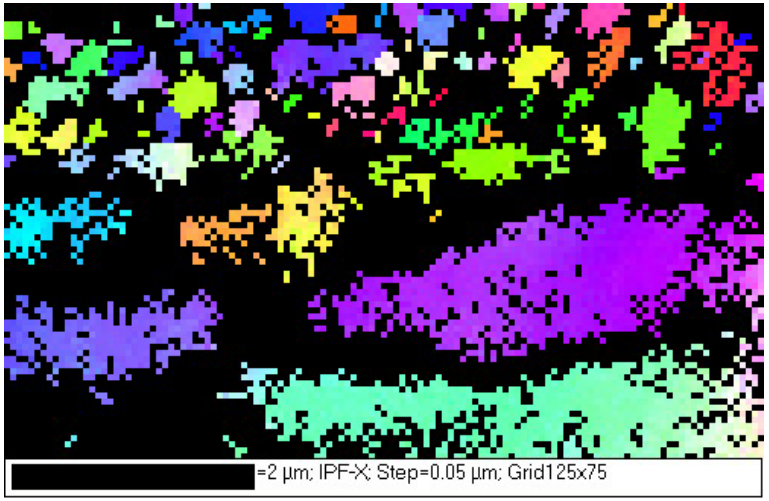
# I. M4 Sciences Al 6061-T6




**Equiaxed**

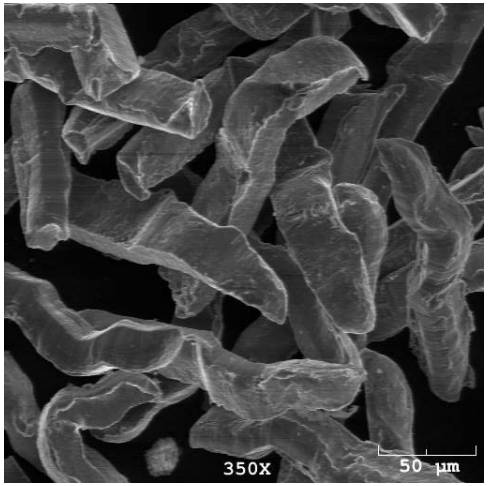
**50 x 50 x 30**




**Needles**

**30 x 100 x 20**






Sandia National Laboratories

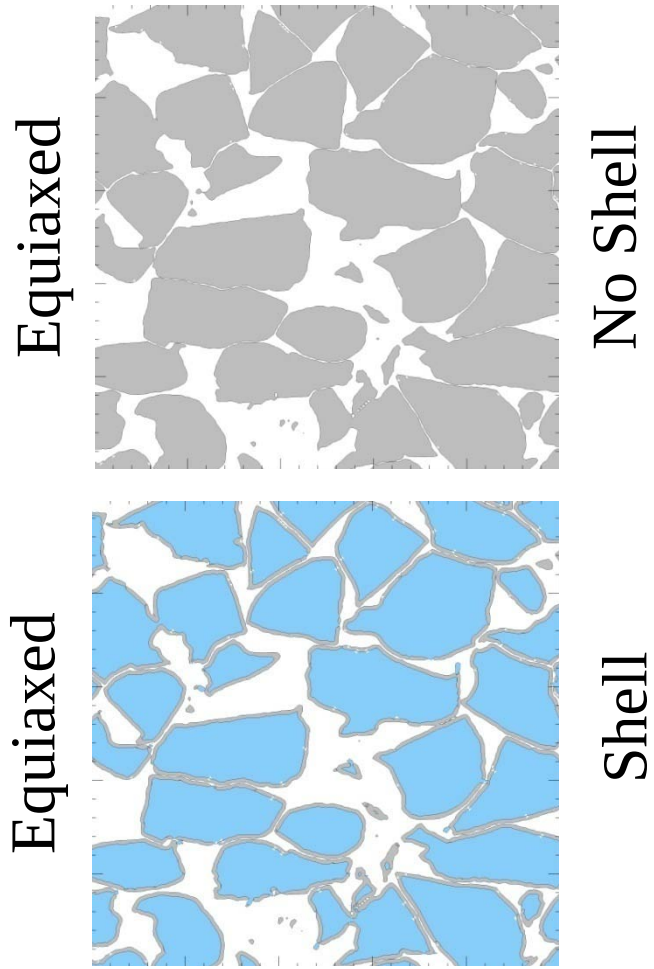
# II. Simulation Environment

- **Particles w/o shell**
  - **Mie Gruneisen EOS**
    **$\rho_0$=2.703 g/cm$^3$, $C_0$=5.22 km/s, S=1.37, $\gamma$=1.97**
  - **Steinberg-Guinan Strength Model**

$$Y = Y_0\left[1+\beta\left(\varepsilon+\varepsilon_i\right)\right]^{\eta}\left(1+\left(\frac{G_P^{'}}{G_0}\right)\frac{P}{\eta^{1/3}}+\left(\frac{G_T^{'}}{G_0}\right)\left(T-300\right)\right)$$

**No Shell $Y_0$ = 0.29 Gpa**

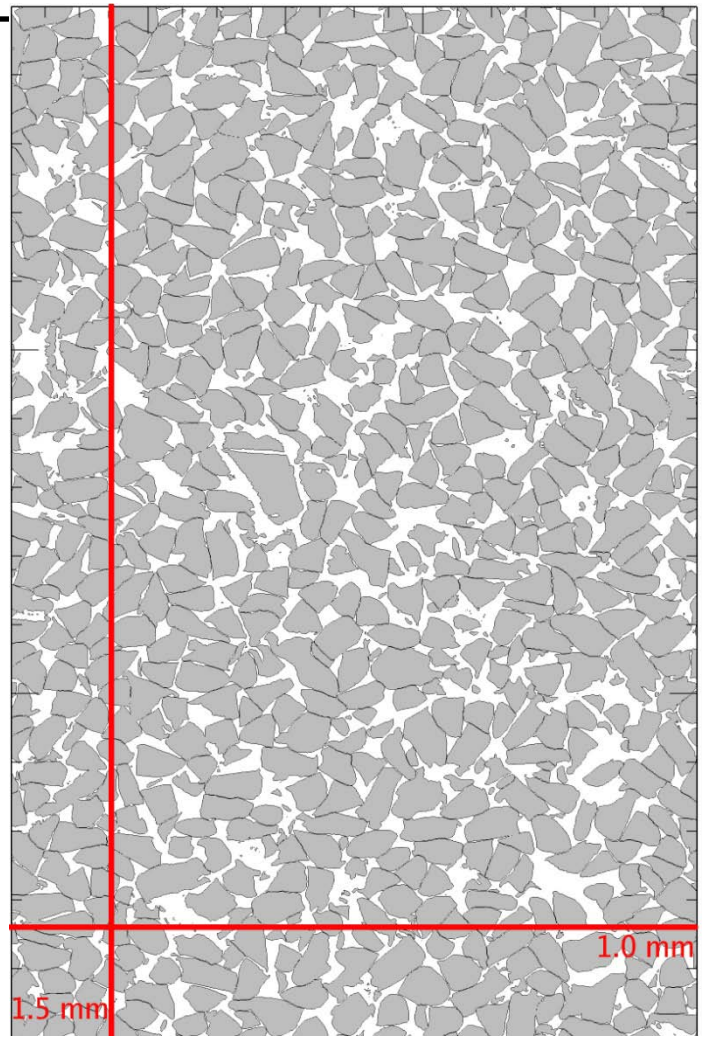
**Shell $Y_0$ = 0.5 Gpa ($Y_0$ ~ $H_V$/3)**



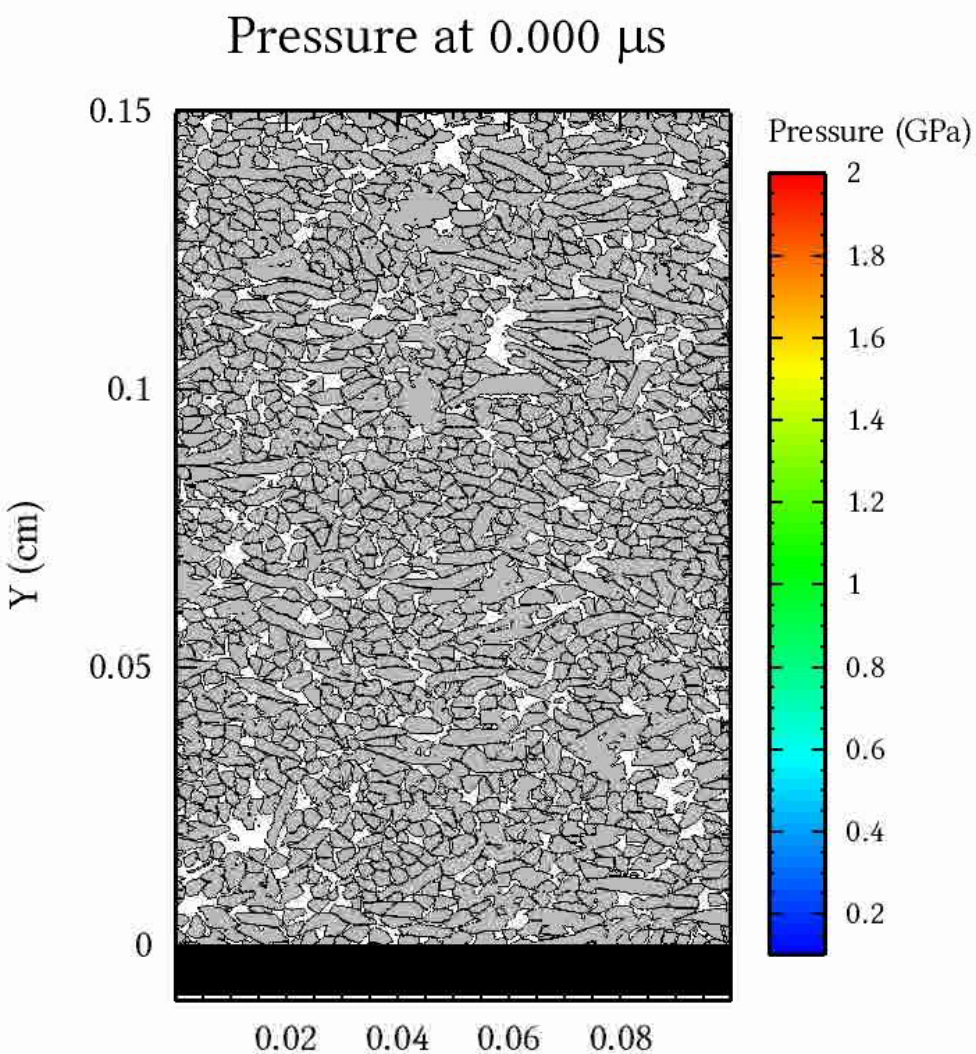

*D.J. Steinberg (1980)*
*Taylor, P.A., CTH Reference Manual: The Steinberg-Guinian-Lund Viscoplastic Model.*

# II. Simulation Environment

- CTH
  - Eularian/Lagrangian
    - Accommodate large strains
    - ~ 1.3μm square mesh
  - Parallel Processing
    - 24 processors (SNL)
  - Meso-scale (Particle Level)
    - Deformation and stress transfer
- Initial Density
  - EQ = 73.5 %, NE = 75.0% TMD



# II. Simulation Environment

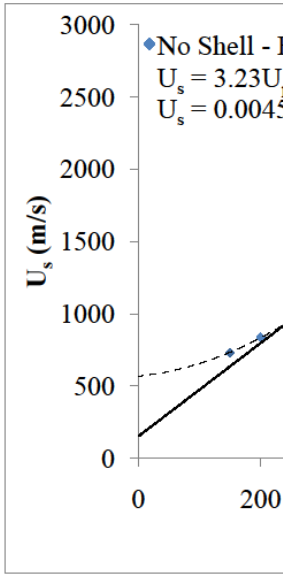


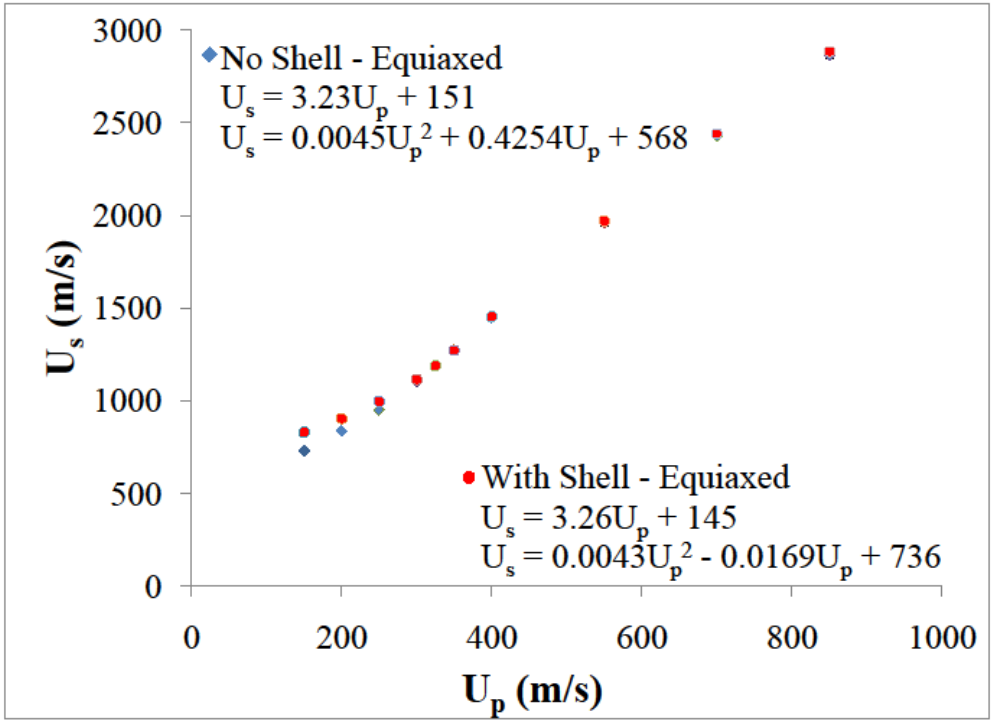

- **Constant $U_p$ (m/s)**
  - **150, 200, 250, 300, 325, 350, 400, 550, 700, 850**
- **(No) Shell effects**
  - **$U_s$ –$u_p$**
  - **P - V**

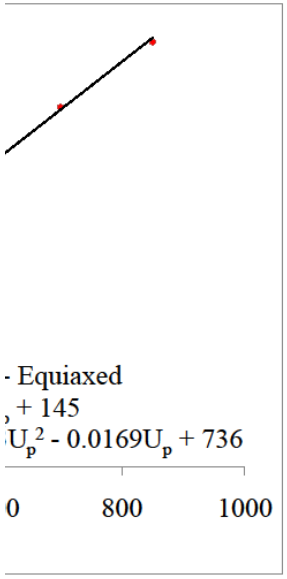
Sandia National Laboratories

# II. $U_S$ - $u_P$

## Equiaxed



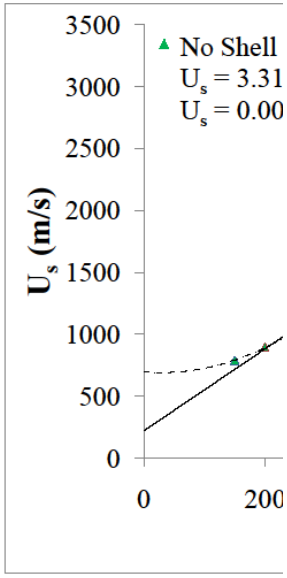



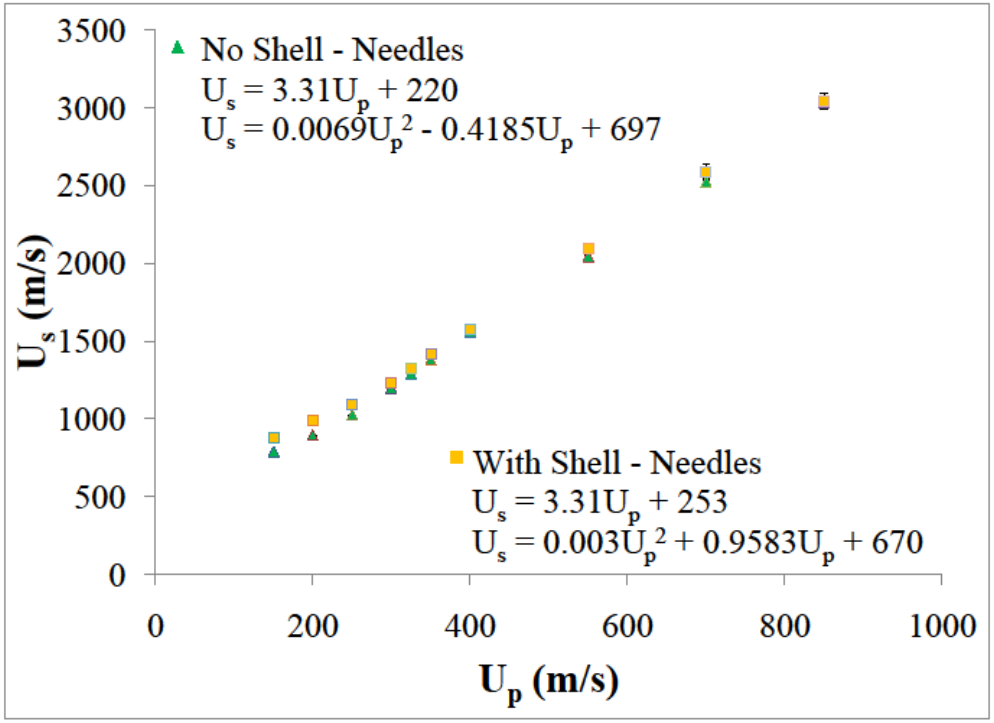


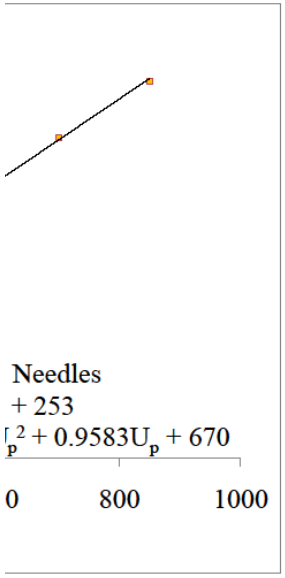

Sandia National Laboratories

# II. $U_S$ - $u_P$

## Needles



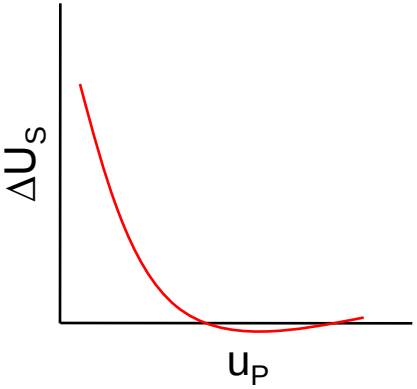






Sandia National Laboratories

# II. $U_S$ - $u_P$

- **Presence of high strength surface layer causes increase in measured $U_S$**
  - **Strength and morphology effect reduction in increased $U_S$ with increasing driver velocity**
    - **Dynamic yield (Steinberg)**
      - **EQ = 325 m/s (min @ 325)**
      - **NE = 300 m/s (min @ 400)**
- **Needles show larger increases in $U_S$**
  - **Aspect ratio**
  - **Hard:Soft EQ = 0.195, NE = 0.270**



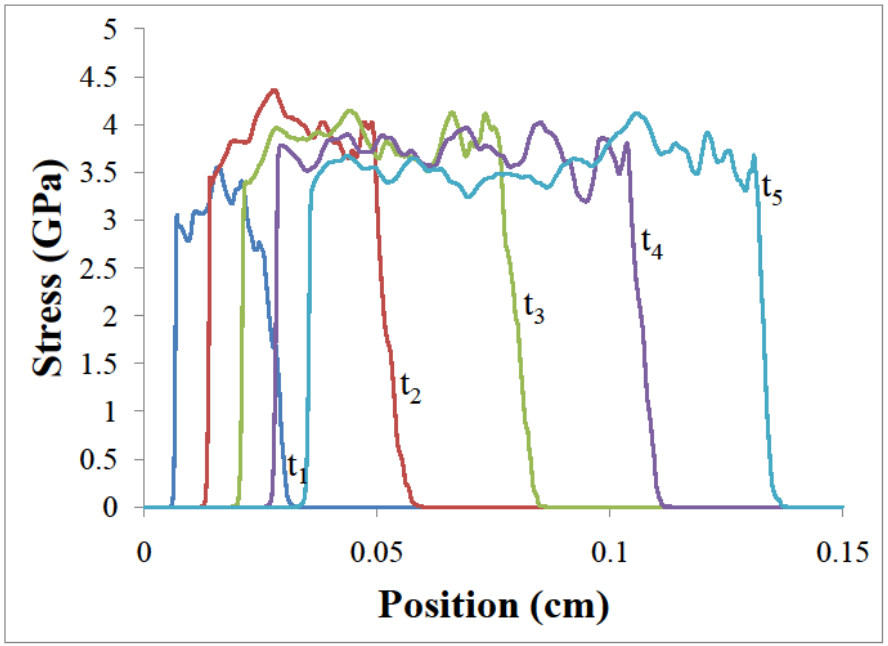

$$Y = Y_0\left[1+\beta\left(\varepsilon+\varepsilon_i\right)\right]^{\eta}\left(1+\left(\frac{G_P^{'}}{G_0}\right)\frac{P}{\eta^{1/3}}+\left(\frac{G_T^{'}}{G_0}\right)\left(T-300\right)\right)$$

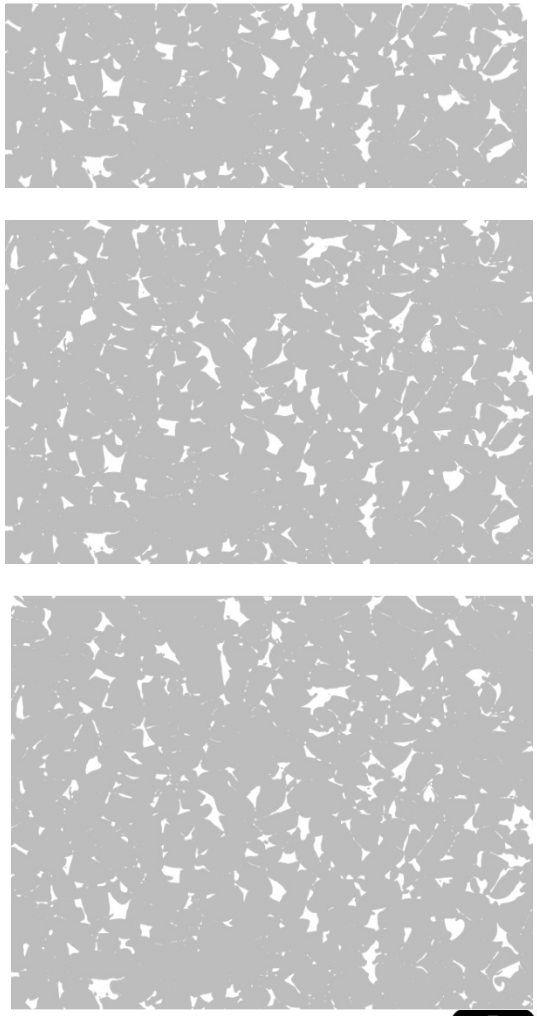


Sandia National Laboratories

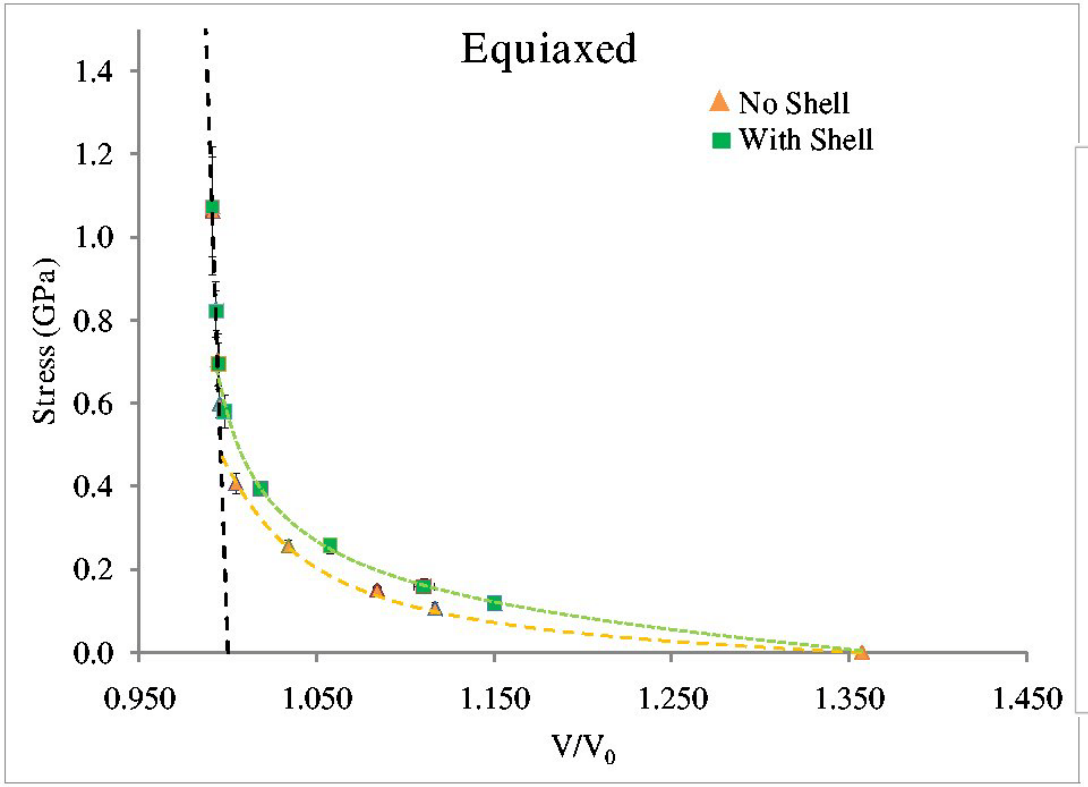
# II. P - V

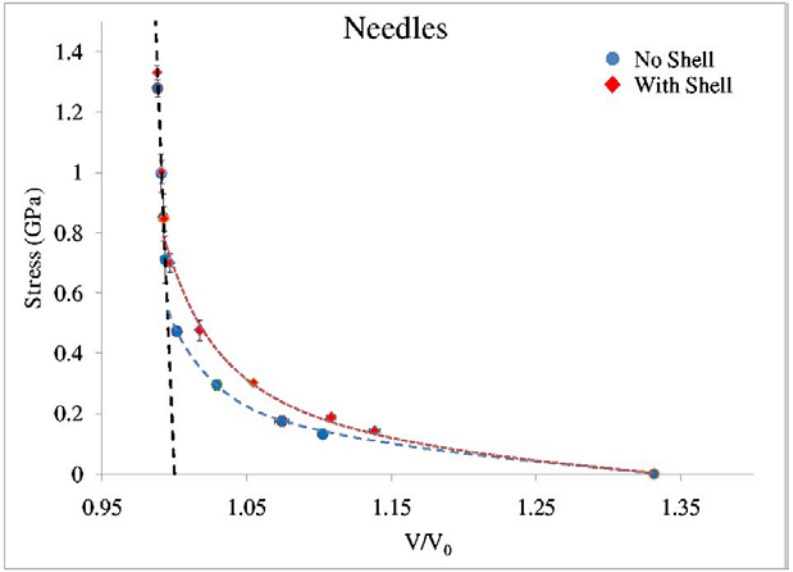
- Pressure histogram
  - average pressure
  - average density



# II. P – V (Crush-up)



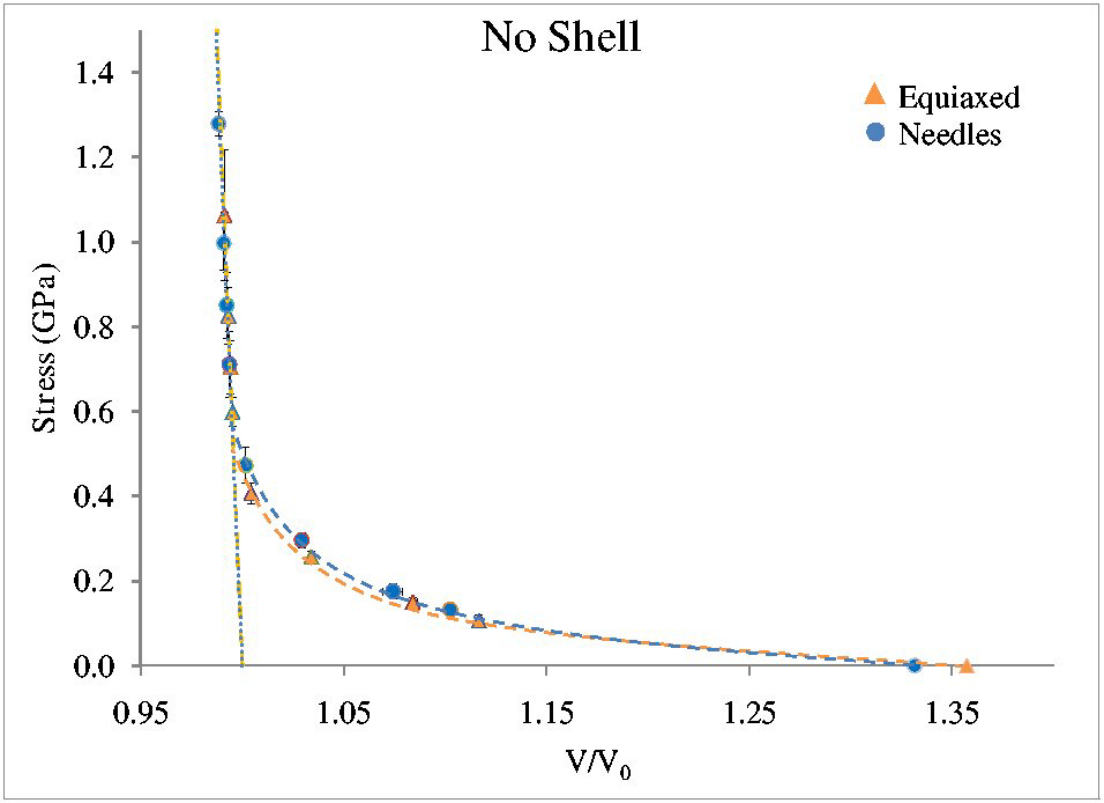



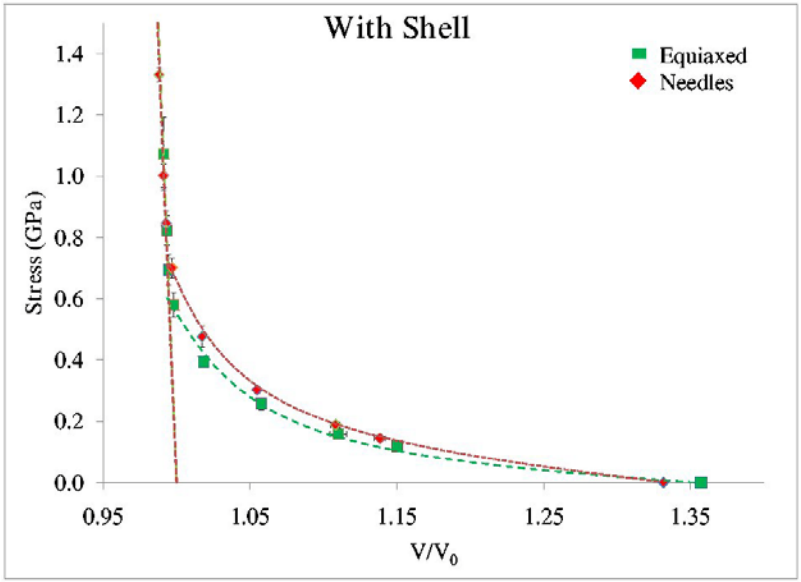

Stiffer response exhibited by shelled particles



Sandia National Laboratories

# II. P – V (Crush-up)




Needles exhibit stiffer response

- exacerbated by presence of shell (EQ=.186, NE=.270)



Sandia National Laboratories

# II. P – V

## Higher compression than predicted from McQueen

$$P = \frac{[2V - \gamma(V_0 - V)]C^2(V_0 - V)}{[2V - \gamma(V_{00} - V)][V_0 - S(V_0 - V)]^2}$$

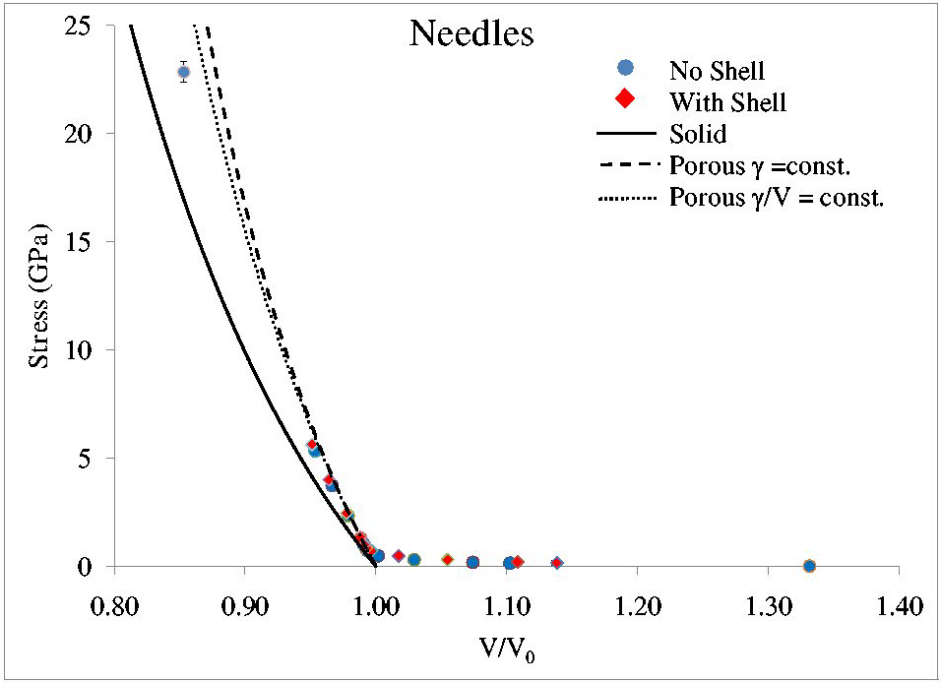
Assumptions:

- Surface energy of particles neglected
- γ is same for porous and solid at same volume

$$\frac{\gamma}{V} = \frac{\gamma_0}{V_0} = \frac{\gamma_{00}}{V_{00}} = const.$$

Consideration:

- Homogeneous/heterogeneous temperature distribution






Sandia National Laboratories

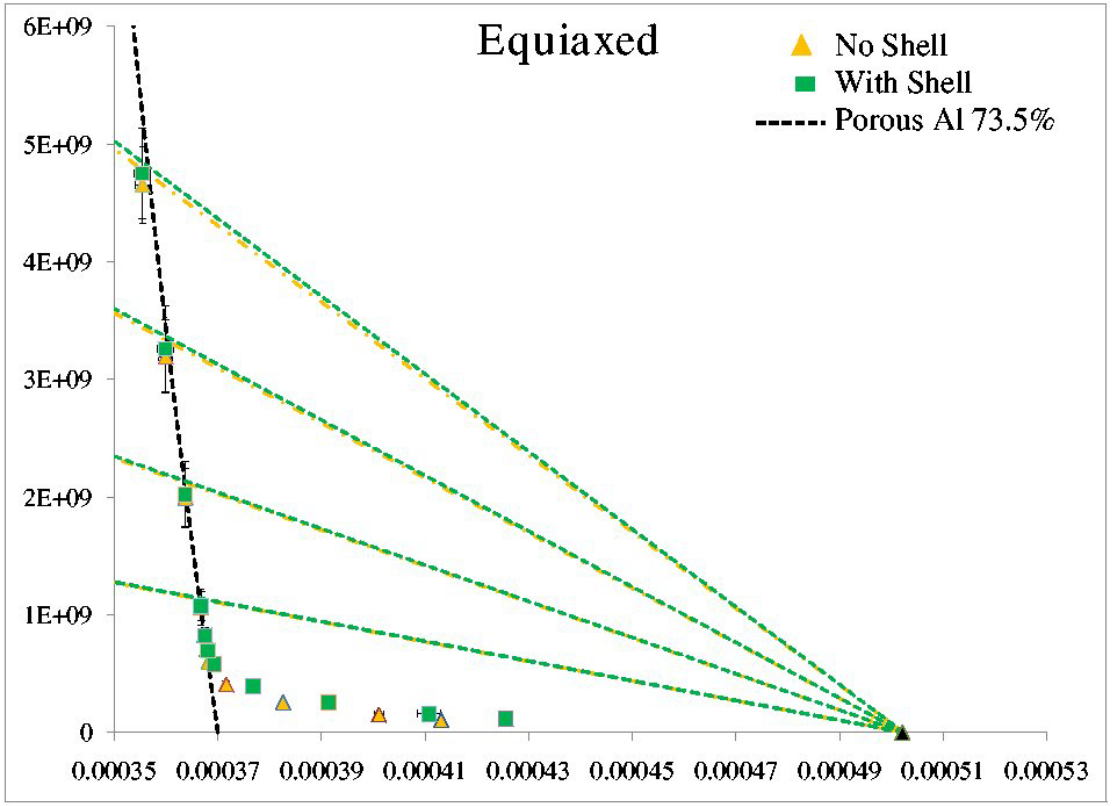
# II. P – V

## Porous Hugontiot*

$$P = \frac{\left[2V - \gamma\left(V_0 - V\right)\right]C^2\left(V_0 - V\right)}{\left[2V - \gamma\left(V_{00} - V\right)\right]\left[V_0 - S\left(V_0 - V\right)\right]^2}$$

$$P(calc) = \rho_{00} U_S u_P$$

| EQ No Shell | | EQ With Shell | |
|---|---|---|---|
| P (calc) | P (meas) | P (calc) | P (meas) |
| 0.169 | 0.105 | 0.199 | 0.1181 |
| 0.218 | 0.150 | 0.248 | 0.1580 |
| 0.333 | 0.256 | 0.360 | 0.2570 |
| 0.473 | 0.407 | 0.497 | 0.3940 |
| 0.658 | 0.598 | 0.666 | 0.5800 |
| 0.772 | 0.704 | 0.769 | 0.6940 |
| 0.887 | 0.826 | 0.886 | 0.8220 |
| 1.154 | 1.063 | 1.158 | 1.0720 |
| 2.150 | 1.994 | 2.158 | 2.0230 |
| 3.385 | 3.193 | 3.401 | 3.2580 |
| 4.847 | 4.650 | 4.880 | 4.7490 |



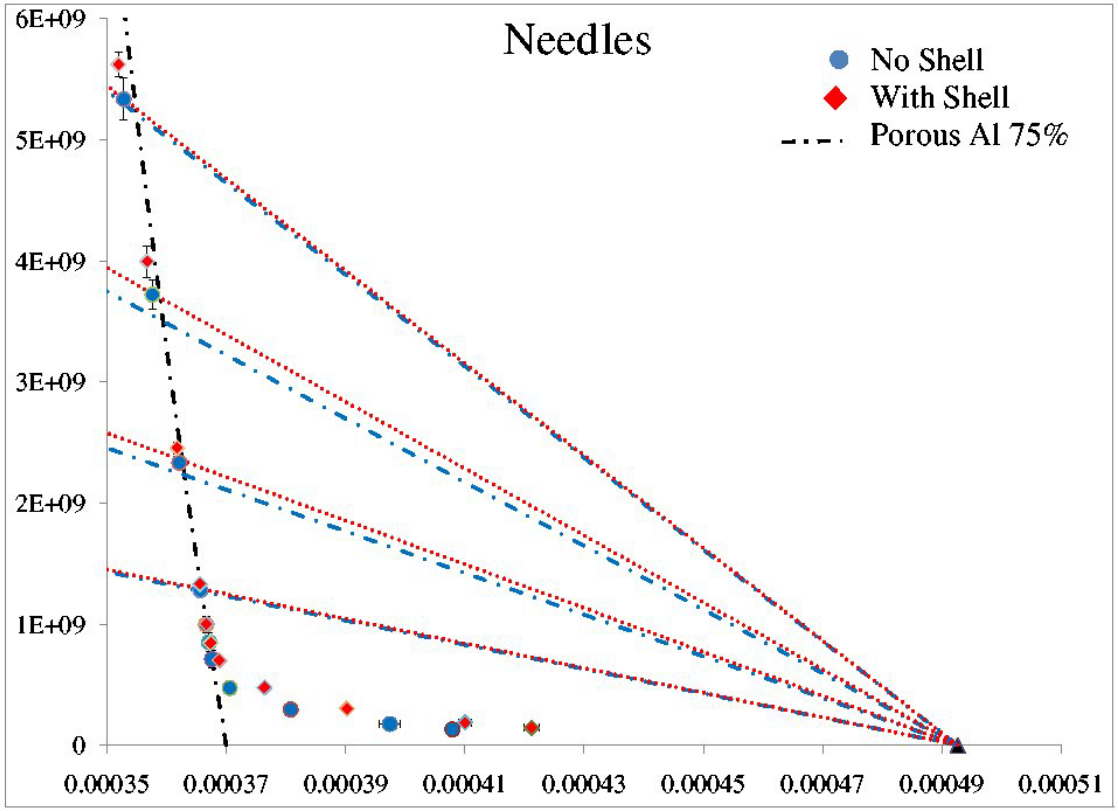

Calculated stress over predicts measured stress over entire range

*R.G. McQueen, et al. (1970)

# III. P – V

$$P(calc) = \rho_{00} U_S u_P$$

| NE No Shell | | NE With Shell | |
|---|---|---|---|
| P(calc) | P(meas) | P(calc) | P(meas) |
| 0.188 | 0.132 | 0.228 | 0.144 |
| 0.240 | 0.175 | 0.268 | 0.188 |
| 0.363 | 0.296 | 0.402 | 0.302 |
| 0.519 | 0.473 | 0.554 | 0.476 |
| 0.730 | 0.711 | 0.751 | 0.700 |
| 0.852 | 0.850 | 0.873 | 0.846 |
| 0.980 | 0.997 | 1.006 | 1.001 |
| 1.267 | 1.279 | 1.275 | 1.331 |
| 2.282 | 2.332 | 2.338 | 2.455 |
| 3.588 | 3.720 | 3.679 | 3.995 |
| 5.230 | 5.334 | 5.250 | 5.622 |




Calculated stress transitions from over to under prediction of measured stress



Sandia National Laboratories

# III. Concluding Remarks: $U_S$-$u_P$

- **Piecewise EOS**
  - **Quadratic (150-300 m/s), Linear (300-850 m/s)**
- **Surface layer causes increase in $U_S$**
  - **More prevalent at low $u_P$**
- **$\Delta U_S$ decreases with increasing driver velocity $u_P$**
  - **Minimum depends on Steinberg $\sigma_{YS}$ and morphology**
- **Larger increase in $\Delta U_S$ for needles**
  - **Higher aspect ratio, increased amount of surface layer**



Sandia National Laboratories

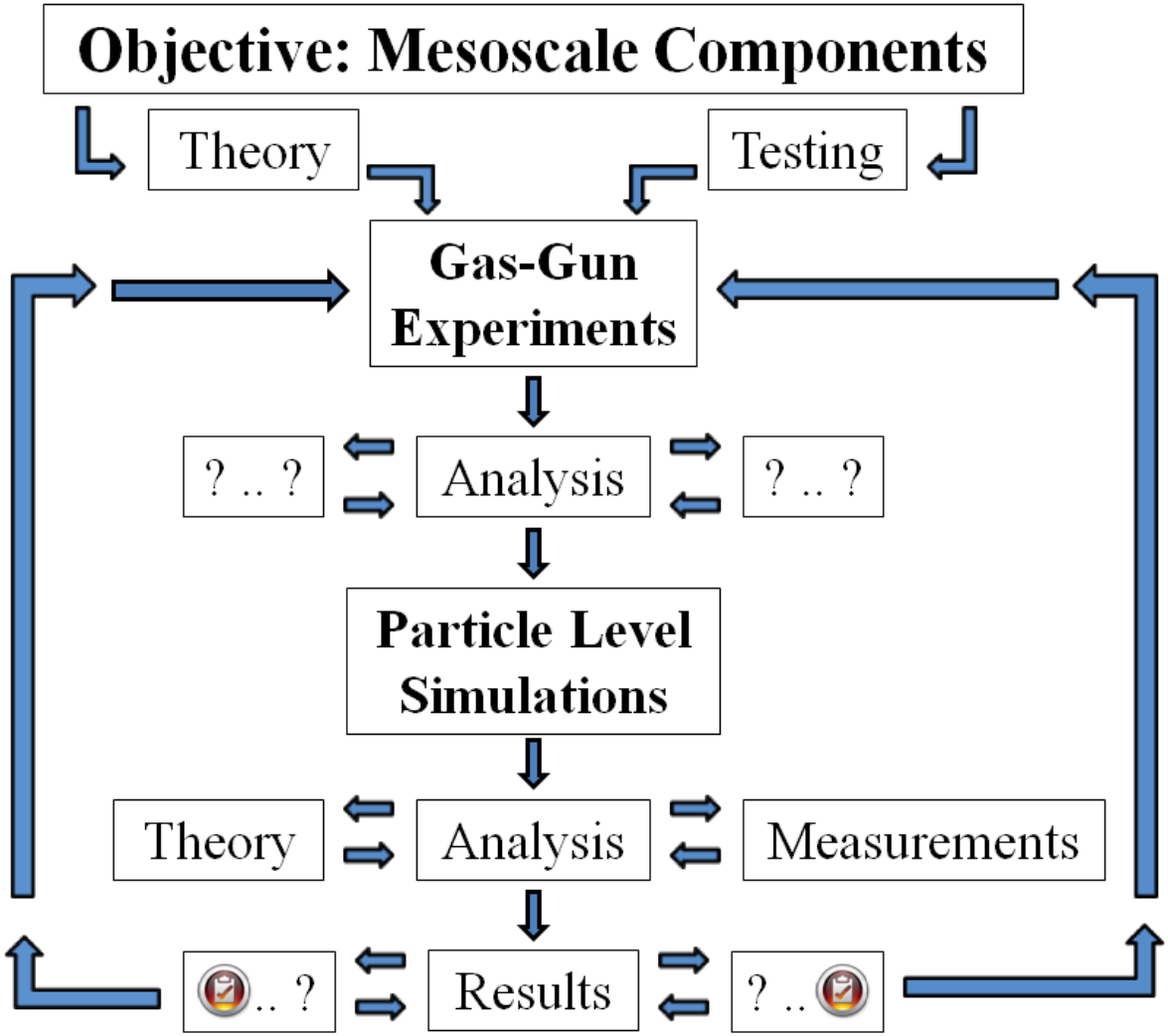
# III. Concluding Remarks: P-V

- Stiffer response for shelled particles
- Morphology influenced P-V response
  - Needles exhibit stiffer response
- Differences between measured and calculated porous Hugoniot
  - Lower volume measured then predicted
    - Assumptions in calculations
    - Distribution of energy/temperature
  - EQ: measured P below calculated (known $U_S$,$u_P$)
  - NE: measured P transitions, under then over



Sandia National Laboratories

# IV. Concluding Remarks



# Questions?

**Anthony Fredenburg**
**gth795c@mail.gatech.edu**
**(404)-385-2851 (GT)**
**dafrede@sandia.gov**
**(505)-845-0742 (SNL)**

- **Subtitle 24 pt**
  - **Second level 22 pt**
    - **Third level 20 pt**
      - **Fourth level 18pt**
        - **Fifth level 18pt**