Catastrophic Interface Debonding in Energetic Materials

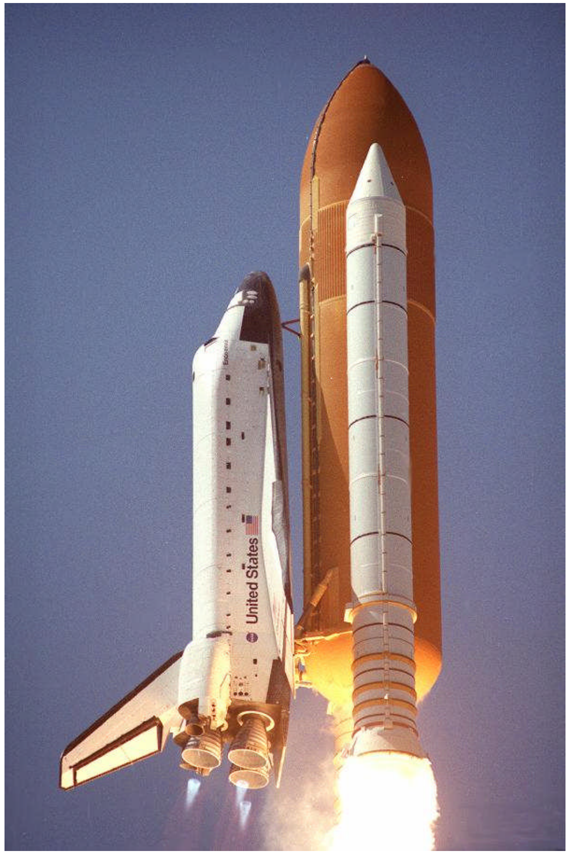
Henry Tan

Lecturer in Explosion Engineering

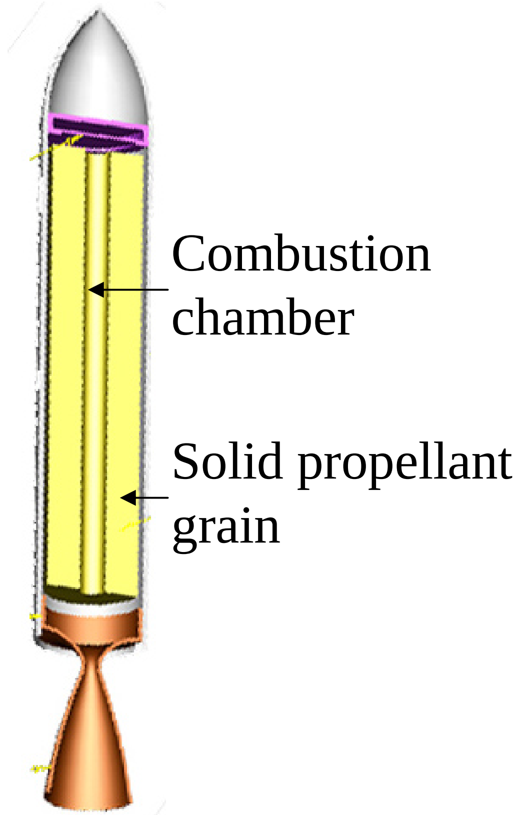
School of Mechanical, Aerospace and Civil Engineering

University of Manchester

Solid Propellant Rocket
Burning Rate – Chamber Pressure



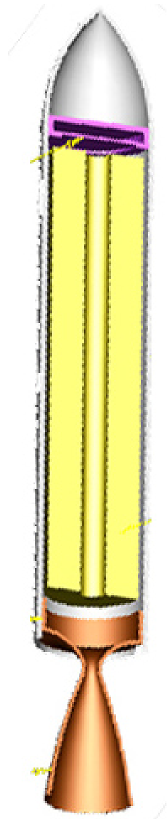
NASA space shuttle



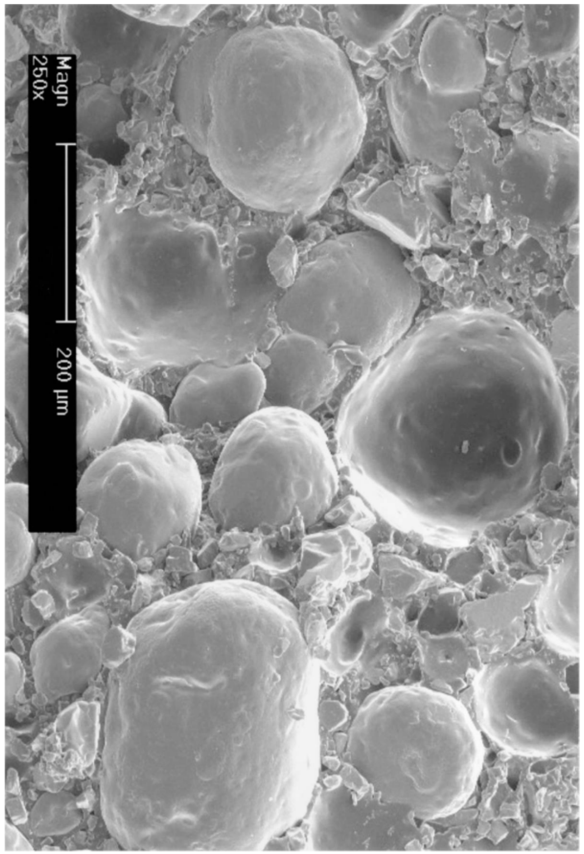
Solid propellant rocket

- The burning rate increases with the chamber pressure, and the chamber pressure increases with the burning rate.

Microstructure of Solid Propellant



Solid rocket

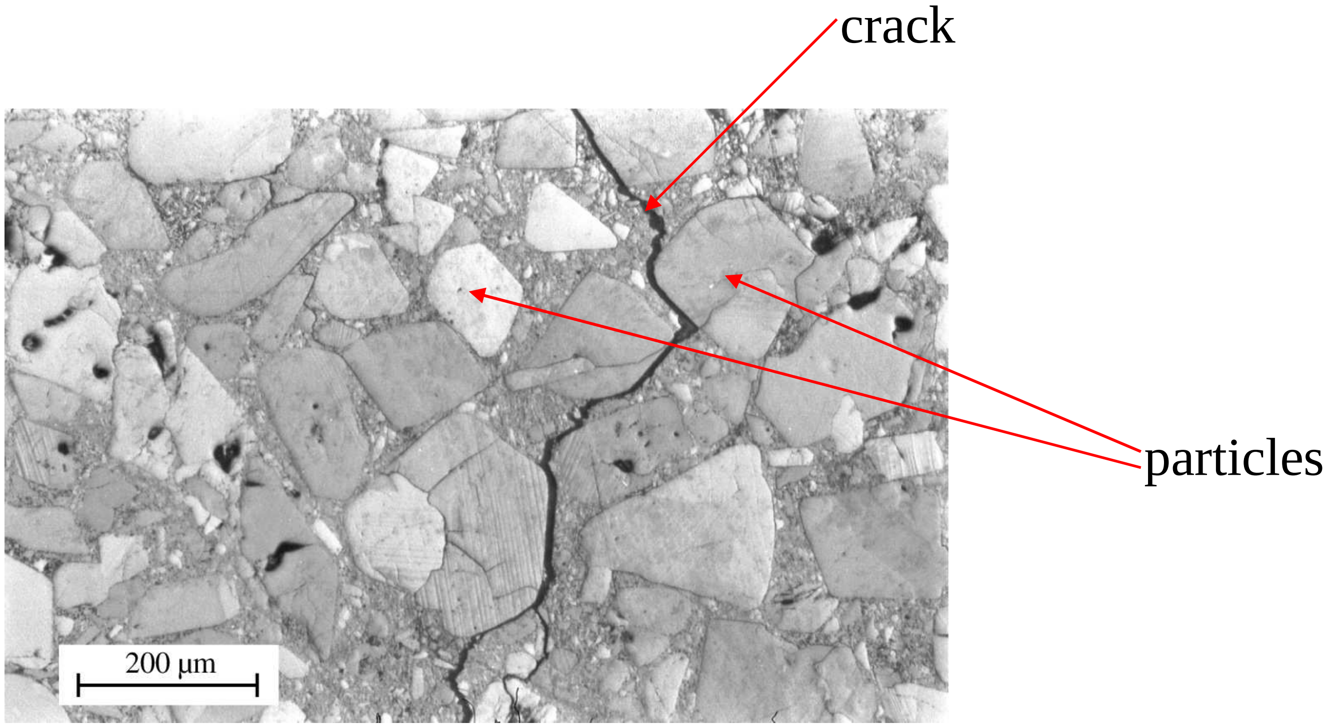


Microstructure of solid propellant material
Ide *et al*., 1999

- Particle/binder with interfaces
- Bimodal particle size distribution
- Large particle volume fraction

- Fracture mainly along interfaces

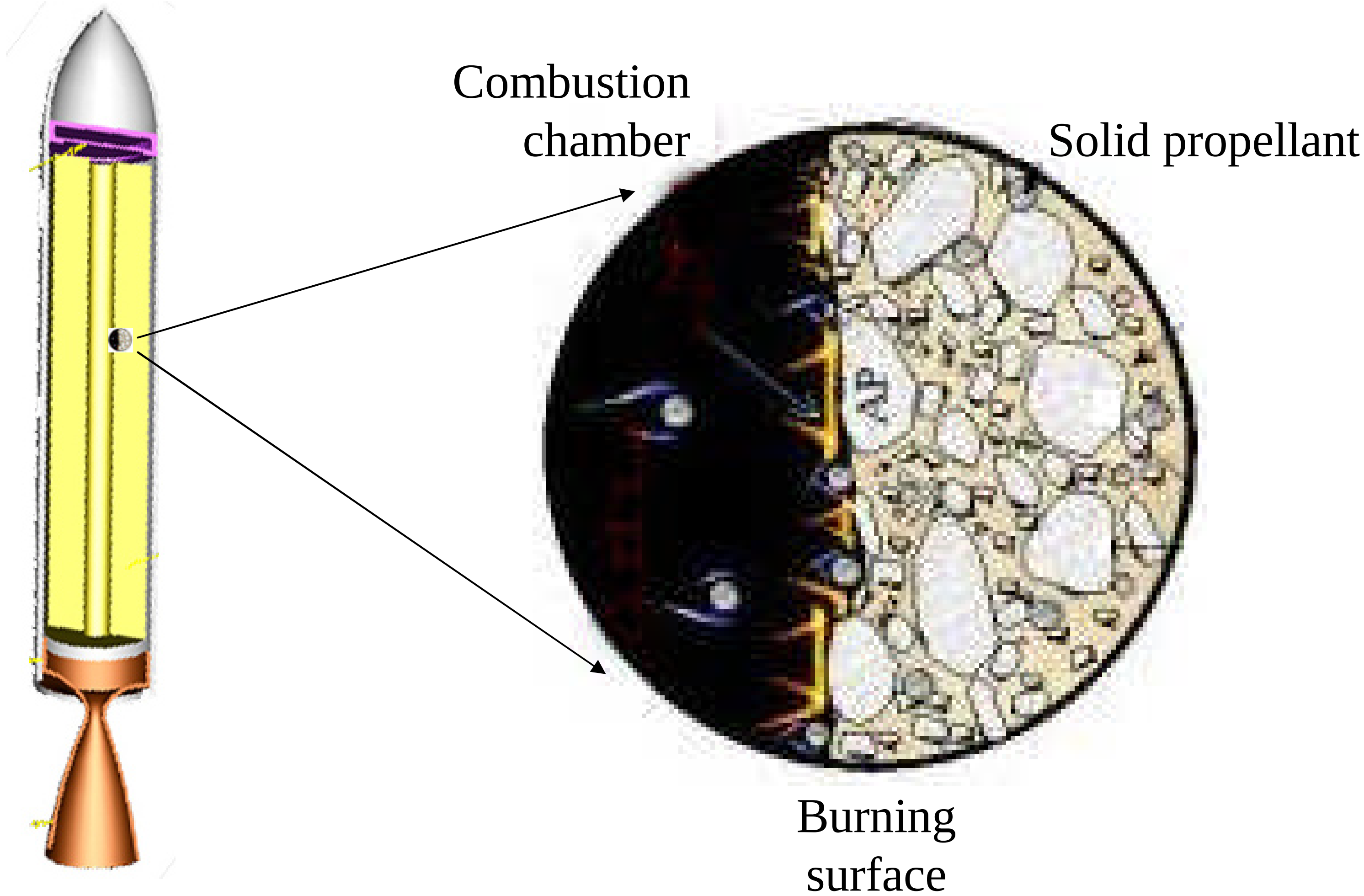
Crack Propagation along Particle/Binder Interfaces



Rae *et al*. 2002. Cavendish Laboratory, Cambridge

- Cracks propagate mainly through interface debonding.

Pressure – Burn – Microstructure

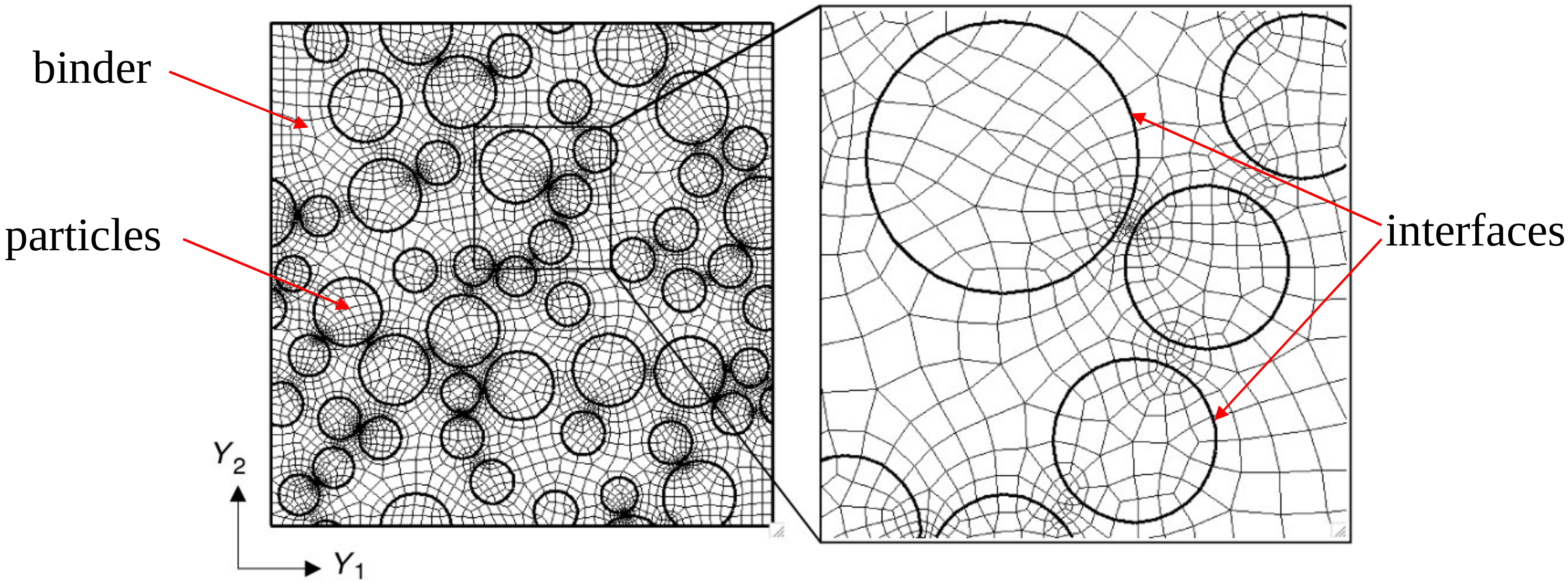


- Relatively small defects, like debonded interfaces and cracks, can lead to catastrophic failure.

Objective

To establish a **stability criterion**
for interface debonding in plastic bonded energetic materials

What Do Simulations Tell Us?

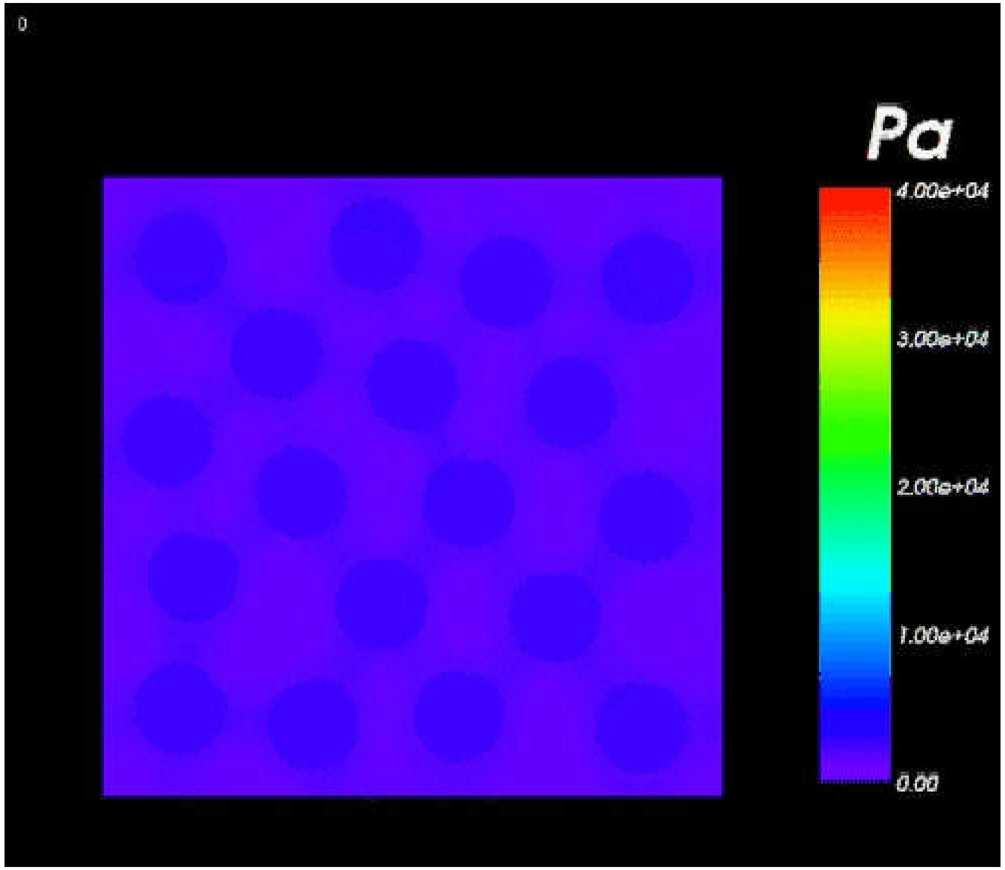


Inglis, Geubelle, Matous, Tan and Huang, 2007, Mech. Mater.

- Macroscopic strain imposed as a body force applied at microscale
- 4-noded cohesive element at interfaces
- Periodic boundary conditions

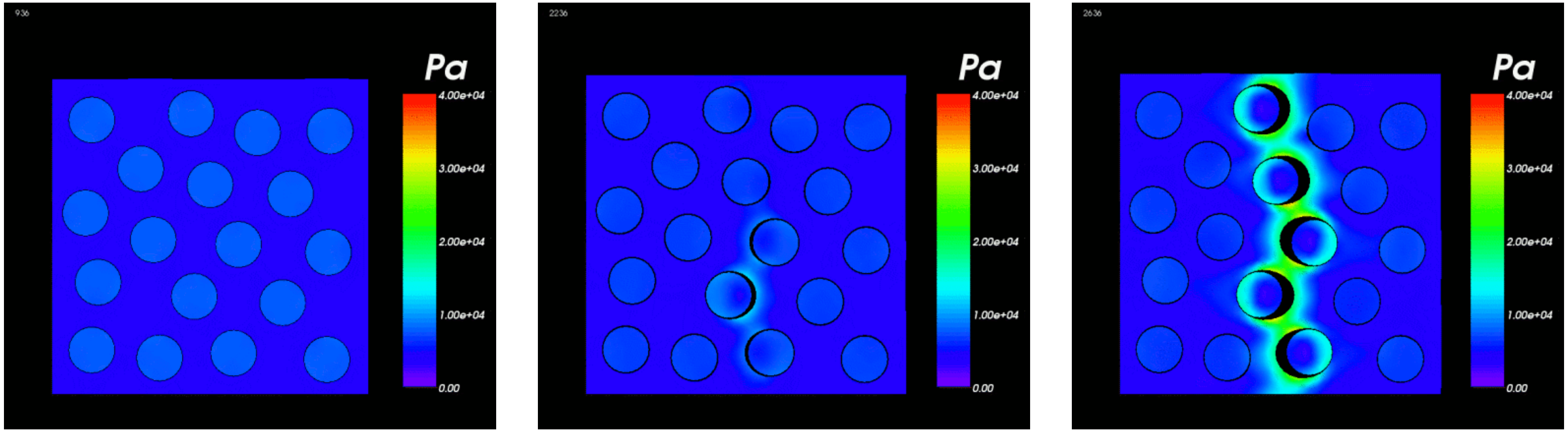
Material Subject to Increased Loading

- Material subjects to equibiaxial strain
- Color-scale represents von Mises stress



Catastrophic Interface Debonding

Increasing equibiaxial load



Uniform debonding

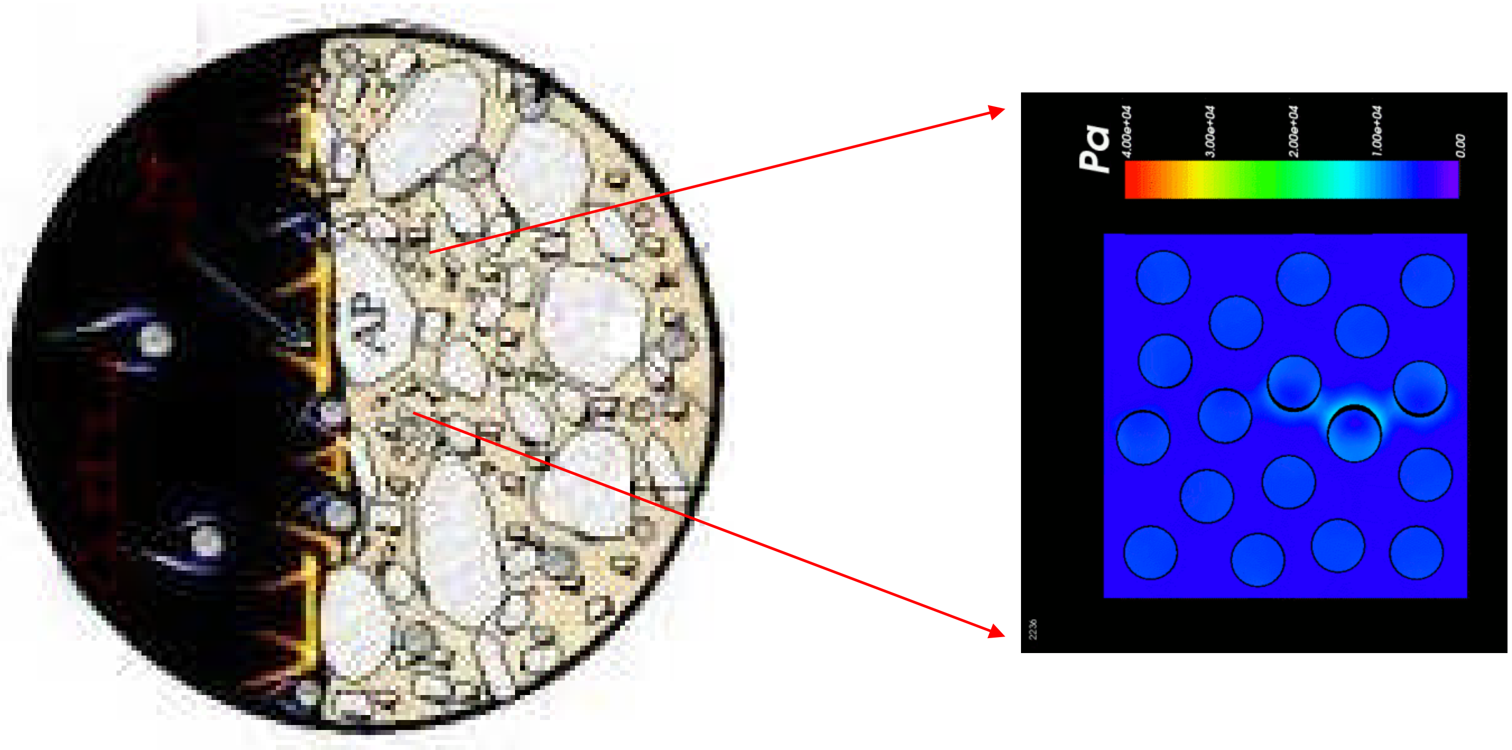
Sudden non-uniform debonding

Collapse of interface debonding
→ Crack formation

- Sudden interface debonding under quasi-static loading

Deflagration to Detonation Transition

Increasing chamber pressure



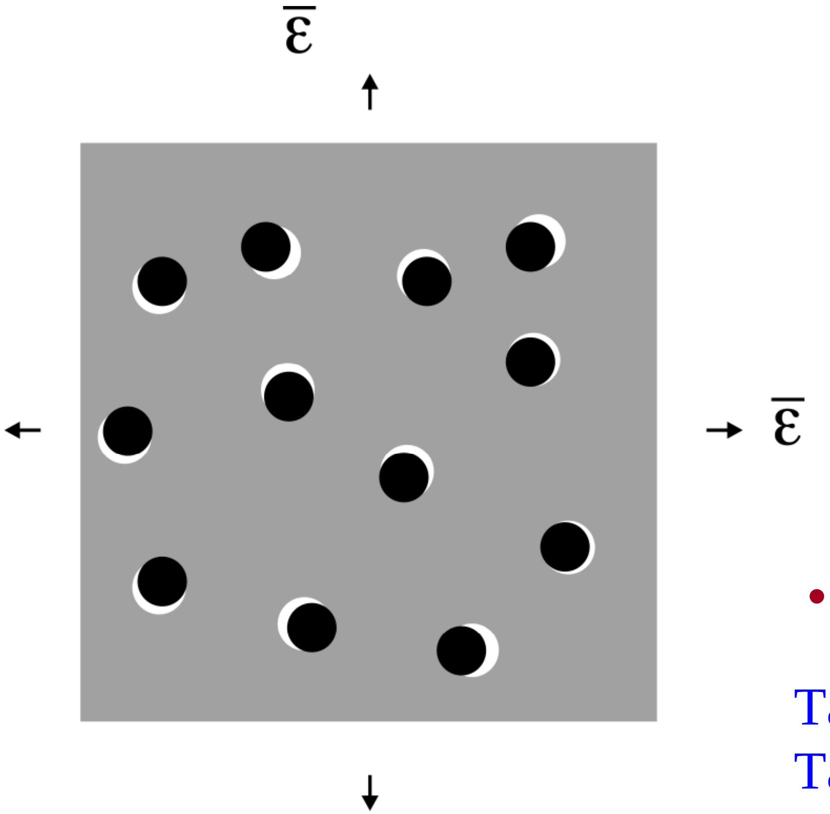
- Sudden interface debonding -> hot spots
- Pressurised cracks

Strain Energy Density in Hydrostatic Tension

interface cohesive energy

$$\Pi\left([\mathbf{u}]\right) = \frac{1}{\Omega}\left\{\frac{1}{2}\int_{\Omega}\sigma_{ij}\left([\mathbf{u}]\right)\varepsilon_{ij}\left([\mathbf{u}]\right)dV + \int_{S_{\text{int}}}\phi\left([\mathbf{u}]\right)dA\right\}$$

strain energy in the matrix and particles



Π is a functional of displacement jump [$\boldsymbol{u}$] at interfaces.

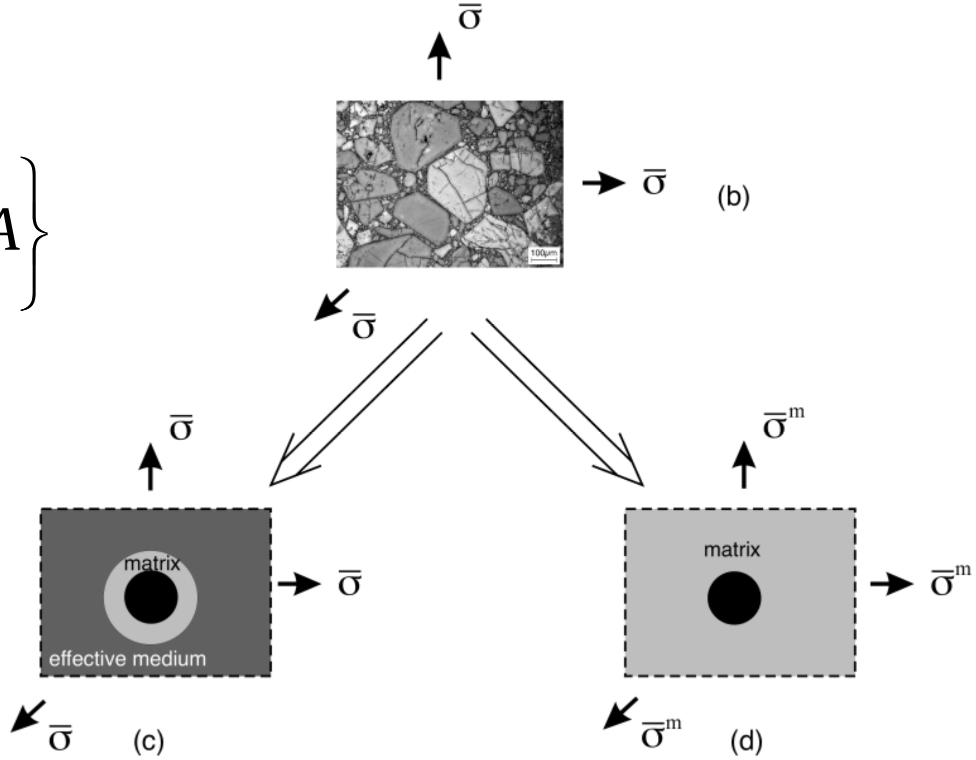
- Determine [$\boldsymbol{u}$] by minimizing $\Pi([\boldsymbol{u}])$

Tan *et al*., 2005. *AIAA*

Tan *et al*., 2006. *Int. J. Multiscale Comput. Eng.*

Homogenization Methods in Micromechanics

$$\Pi = \frac{1}{\Omega}\left\{\frac{1}{2}\int_{\Omega}\sigma_{ij}\varepsilon_{ij}dV + \int_{S_{\text{int}}}\phi dA\right\}$$



Generalized Self Consistent Method

Mori-Tanaka Method

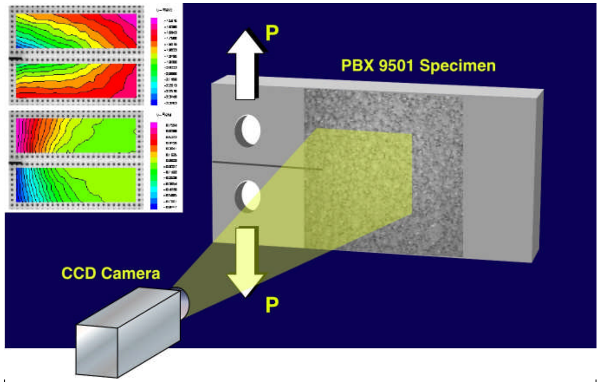
- Mori-Tanaka method is extended to account for nonlinear interface debonding.

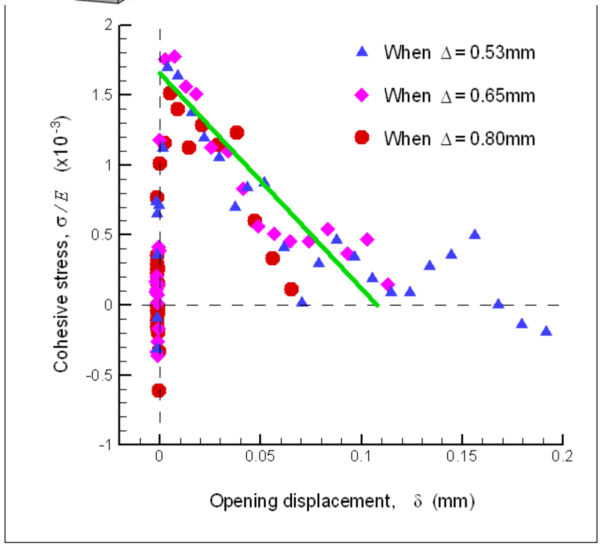
Tan *et al*., 2005. *Int. J. Plasticity*
Tan *et al*., 2007. *Int. J. Fract.*

Determine Interface Cohesive Law for High Explosives

$$\Pi = \frac{1}{\Omega}\left\{\frac{1}{2}\int_{\Omega}\sigma_{ij}\varepsilon_{ij}dV + \int_{S_{\text{int}}}\phi dA\right\}$$

Macroscopic cohesive law

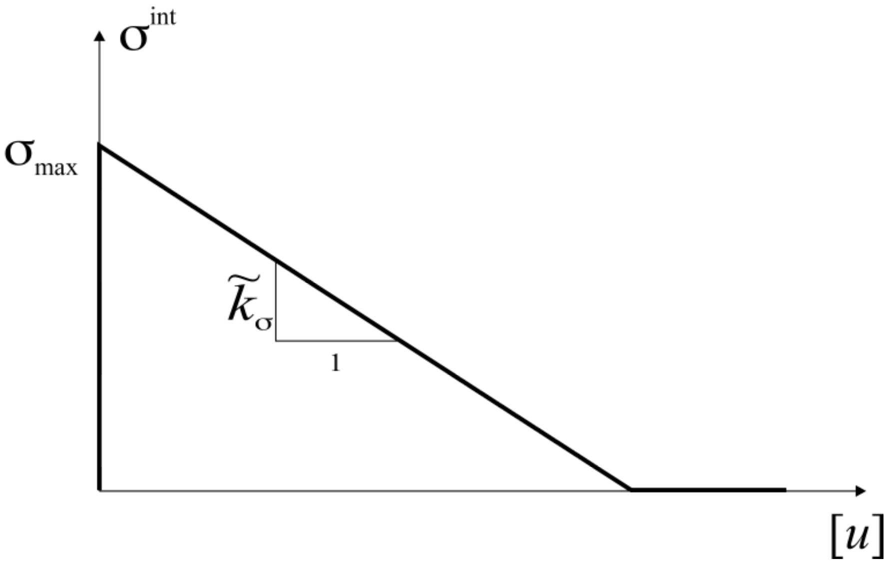




Interface cohesive law

softening modulus: $\tilde{k}_{\sigma} = 17 MPa / mm$

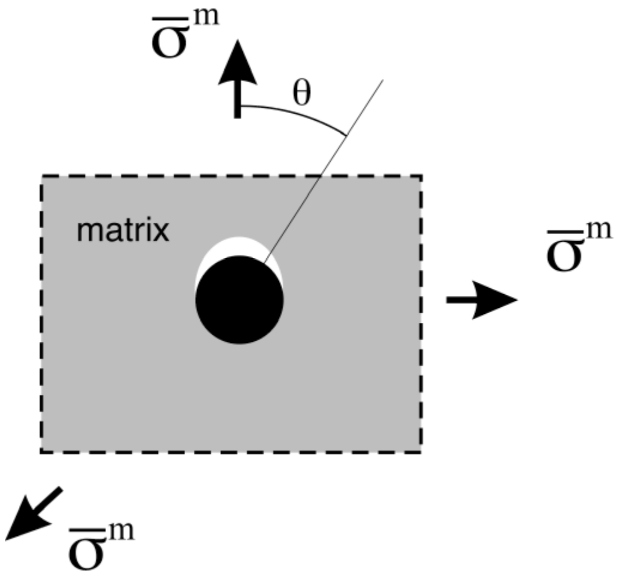
interface strength: $\sigma_{\max} = 1.66 MPa$



Tan *et al*., 2005. *J. Mech. Phys. Solids*

Interface Displacement Jumps

Goal: $$\Pi([\mathbf{u}]) = \frac{1}{\Omega}\left\{\frac{1}{2}\int_{\Omega}\sigma_{ij}([\mathbf{u}])\,\varepsilon_{ij}([\mathbf{u}])\,dV + \int_{S_{\text{int}}}\phi([\mathbf{u}])\,dA\right\}$$



Interface opening $[u]$

$$\frac{[u]}{a} = A_0 + \begin{cases} A_u \cos\theta & \theta \in [0, \pi/2] \\ 0 & \theta \in [\pi/2, \pi] \end{cases}$$

Quadratic Form of Total Potential Energy

- Total potential energy density can be expressed in a **quadratic** form of A_u when subject to hydrostatic loading

$$\Pi(A_u) = c_0 + c_u A_u + c_{uu} A_u^2$$

For rigid particle embedded in incompressible matrix under hydrostatic tension:

$$c_{uu} = \frac{3}{2}\mu_m \left(1.0225 - f - \frac{\tilde{k}_\sigma a}{6\mu_m} \right)$$

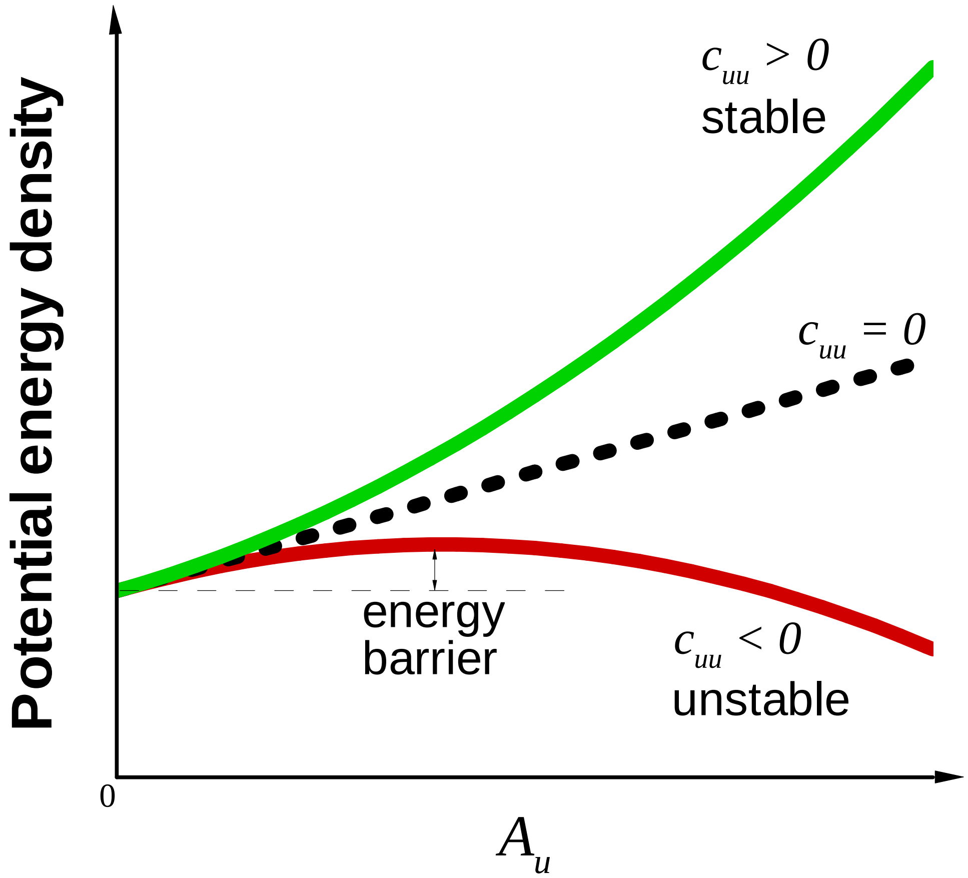
f : particle volume fraction

$\tilde{k}_\sigma$: interface softening modulus

a : particle radius

μ_m : shear modulus of matrix

Stability Criterion for Interface Debonding

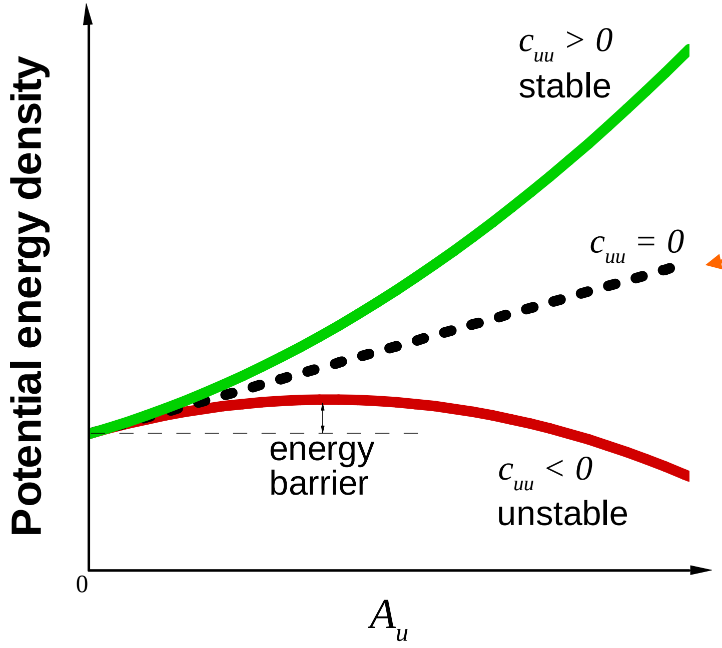


$$c_{uu} = \frac{3}{2}\mu_m\left(1.023 - f - \frac{\tilde{k}_\sigma a}{6\mu_m}\right)$$

$c_{uu} > 0$: stable debonding
$c_{uu} < 0$: unstable debonding

A_u: Magnitude of non-uniform interface opening

Case Study I: Particle Size Effect



critical particle radius

$$a_{cr}^{stability} = 6(1.023 - f)\frac{\mu_m}{\tilde{k}_\sigma}$$

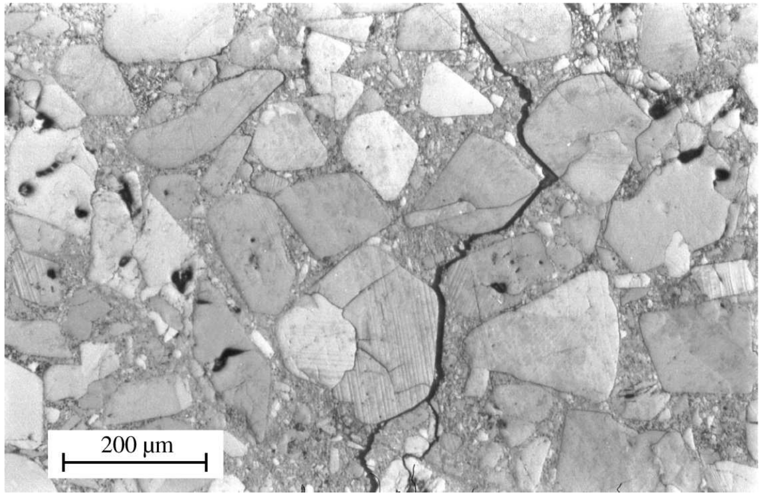
Plastic Bonded Explosives

interface softening modulus:	$\tilde{k}_\sigma = 0.017 MPa/\mu m$	Tan *et al.*, 2005
large particle volume fraction:	$f = 69.5\%$	Skidmore *et al.*, 1997
matrix modulus:	$\mu_m = 0.334 MPa$	Cady *et al.*, 2000

⇨ $a_{cr}^{stability} \approx 39 \mu m$

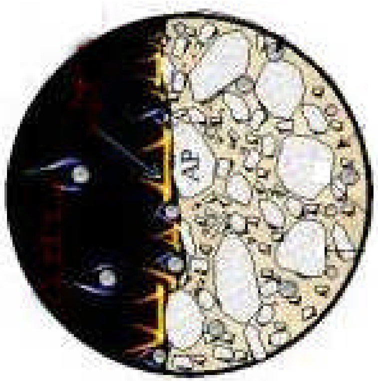
Performance versus Sensibility

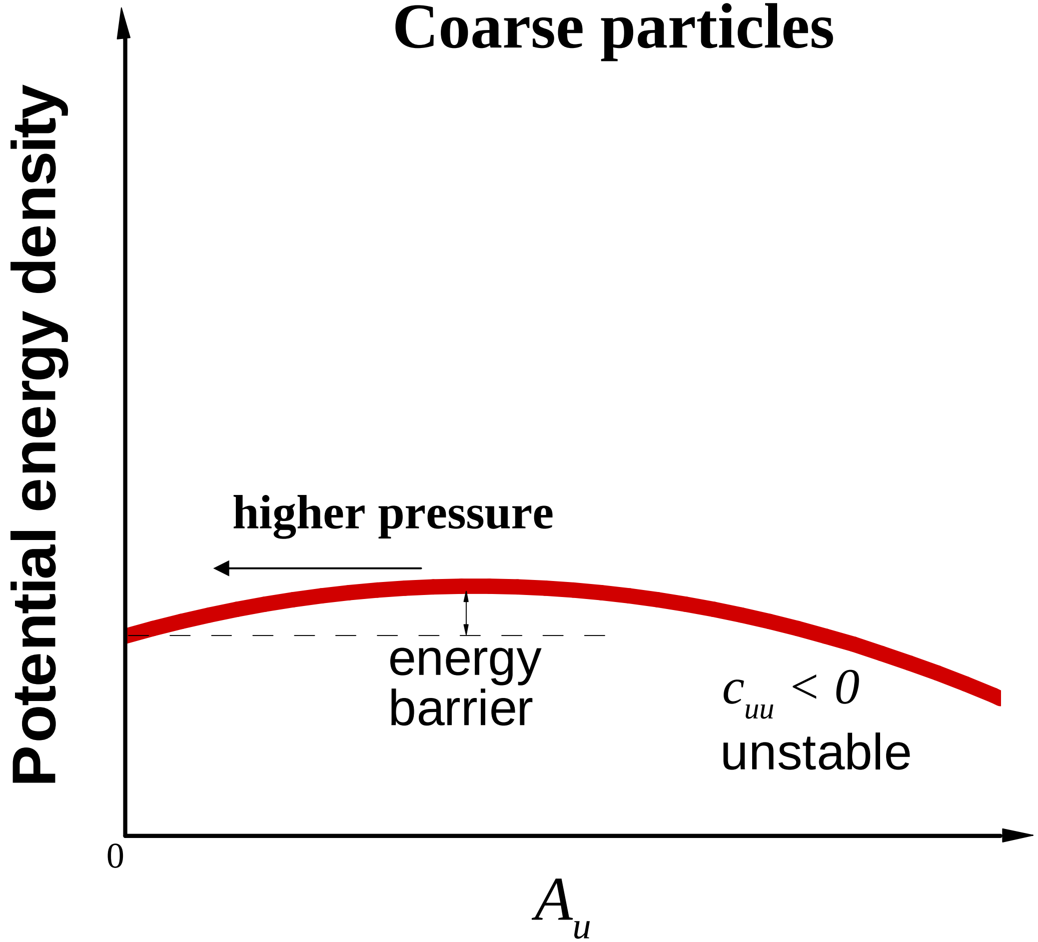
$$a_{cr}^{stability} \approx 39\,\mu m$$



Balancing the performance and sensibility through changing the particle size distribution

Size Effect on DDT



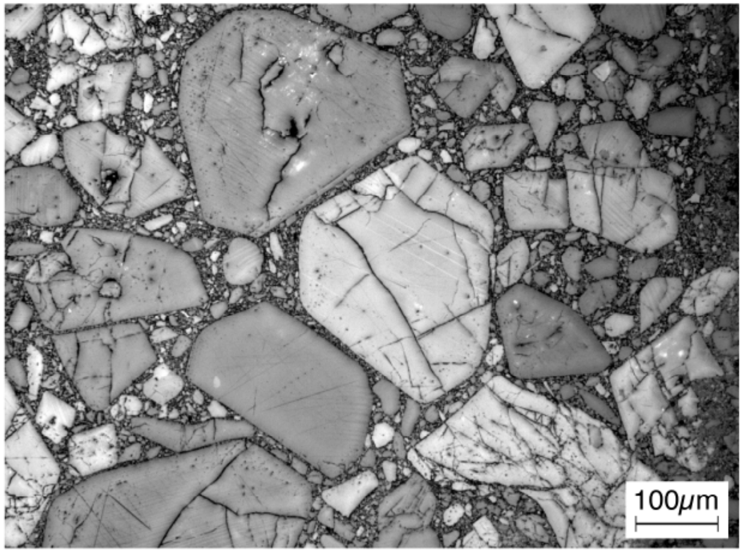


→ **Deflagration to Detonation Transition (DDT)**

Case Study II: Macroscopic Deformation during Compression

8% volume increase
when HMX particles transfer
from β-phase to δ-phase.

PBX 9501 High Explosive



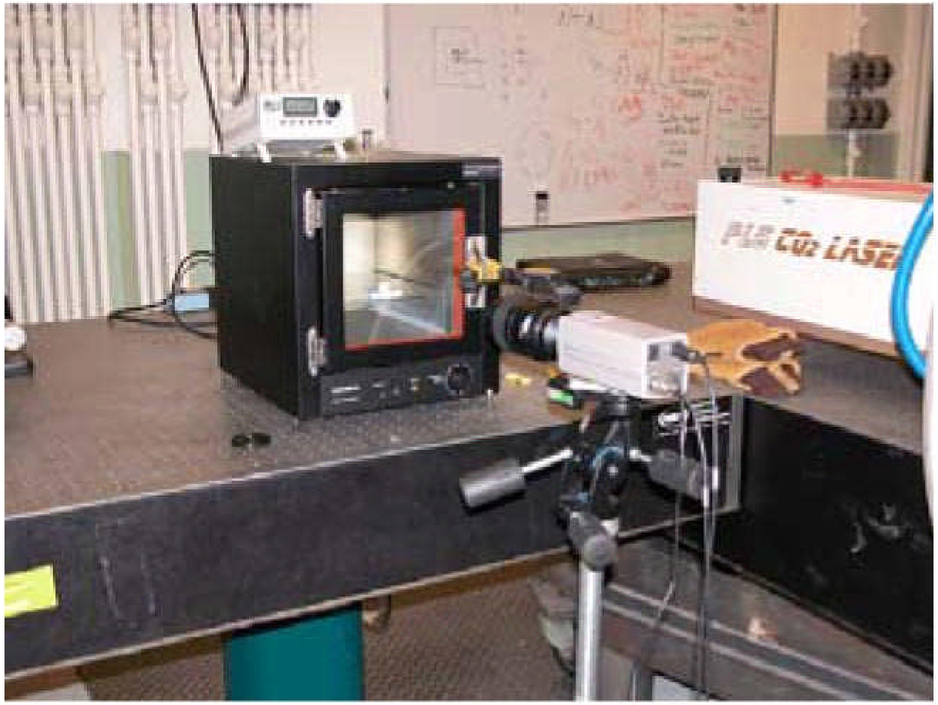
$$a_{cr}^{stability} \approx 39\mu m$$

Average radius of coarse particles is 125μm.

⇨

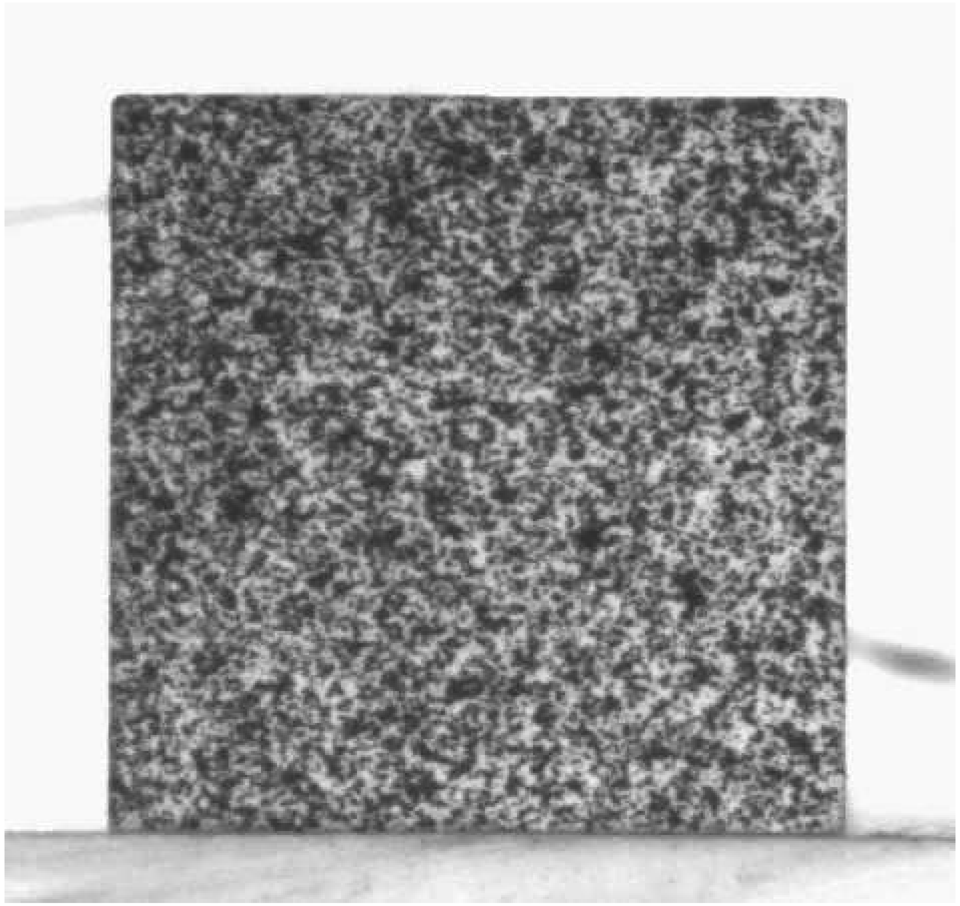
- Microscopically, each particle may debond suddenly in a random direction.
- Macroscopically, deformation field is **chaotic**.

Experimental Setup for
Slow Heating of PBX 9501 Sample

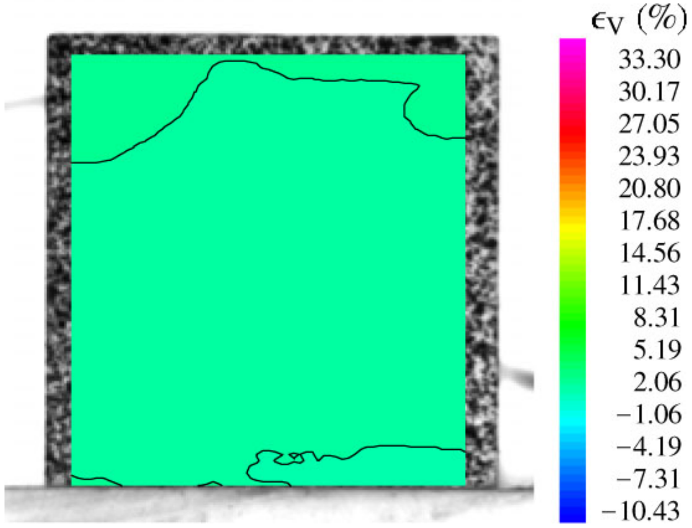


- Cubic sample of size 12.7mm
- Free standing sample
- Temperature ramps from 33ºC to 195ºC in one hour

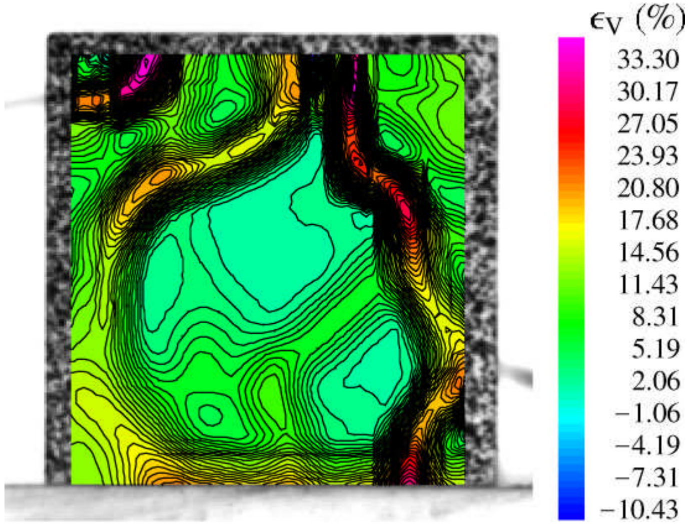
Evolution of the Deformation Field



Strain Field



below transformation temperature

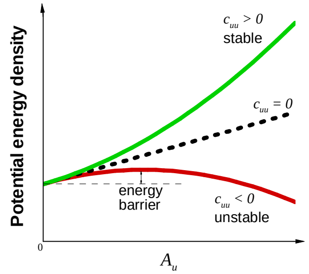


around transformation temperature

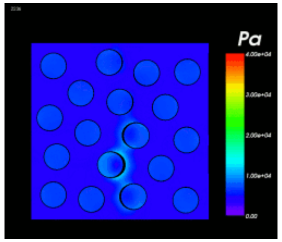
- low strain -> chaotic deformation field

Summary

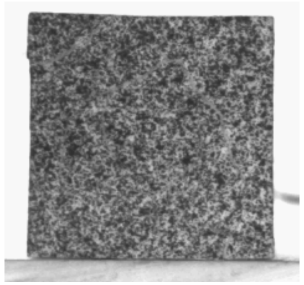
- A stability criterion for interface debonding is established for energetic composite materials.



- Catastrophic interface debonding is observed in numeric simulations.



- Catastrophic interface debonding contributes to the chaotic deformation during the phase transformation of HMX particles.



- Application: safety of solid rocket propellant.