Material Dynamics

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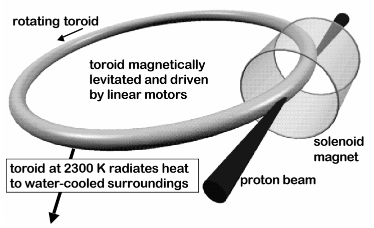
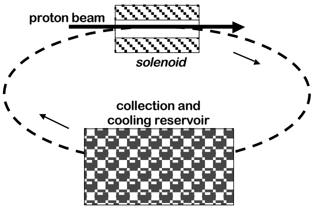
Schematic diagram of the radiation cooled rotating toroidal target



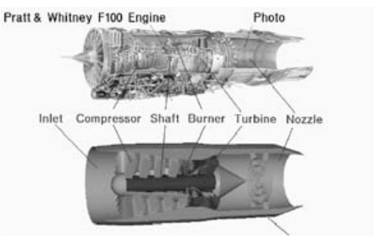
Levitated target bars are projected through the solenoid and guided to and from the holding reservoir where they are allowed to cool



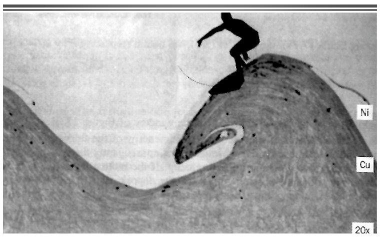
Proposal

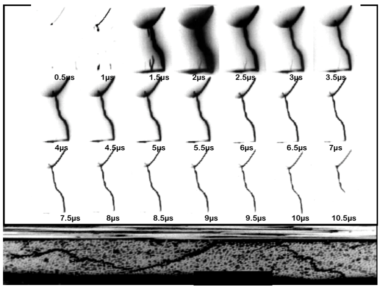
- Investigate, with RMCS, the possibilities of making off-line tests to determine the strength characteristics of tantalum at 2000°C
- Obtain beam time at ISOLDE or ISIS and make measurements
  - *strength characteristics of tantalum at 2000°C*
  - *show if the target breaks after a few pulses*
- Computer model the target and determine the optimum geometry *FGE*

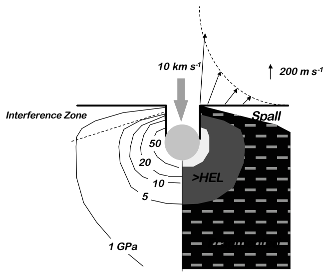
Aerospace

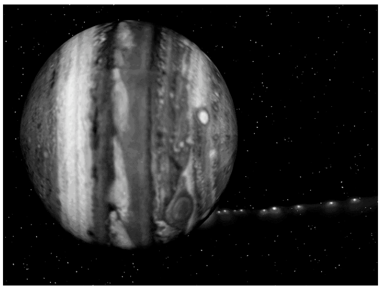


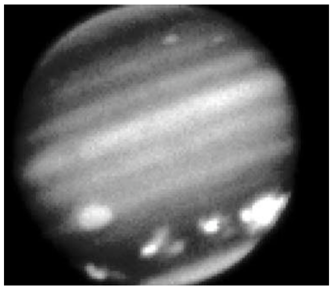
Explosive welding

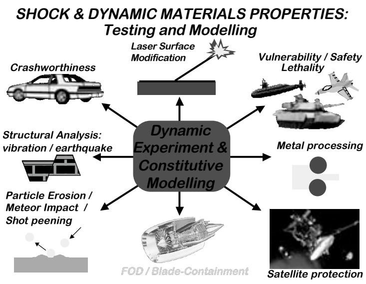


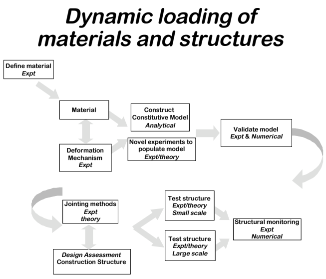

0.5μs
1μs
1.5μs
2μs
2.5μs
3μs
3.5μs
4μs
4.5μs
5μs
5.5μs
6μs
6.5μs
7μs
7.5μs
8μs
8.5μs
9μs
9.5μs
10μs
10.5μs

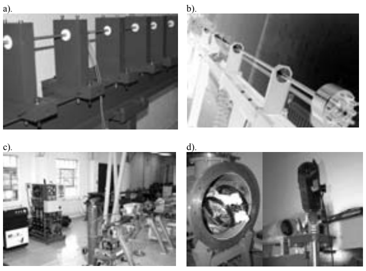

10 km s⁻¹
200 m s⁻¹
Interference Zone
Spall
50
20
10
5
>HEL
1 GPa

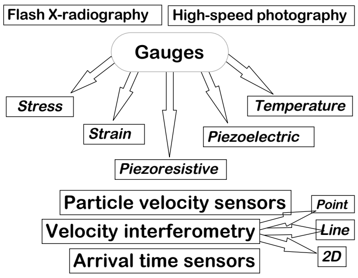




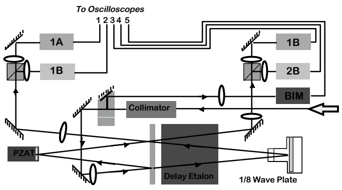

SHOCK & DYNAMIC MATERIALS PROPERTIES:
Testing and Modelling
Laser Surface Modification
Crashworthiness
Vulnerability / Safety Lethality
Structural Analysis: vibration / earthquake
Dynamic Experiment & Constitutive Modelling
Metal processing
Particle Erosion / Meteor Impact / Shot peening
FOD / Blade-Containment
Satellite protection


Dynamic loading of materials and structures
Define material Expt
Material
Construct Constitutive Model Analytical
Validate model Expt & Numerical
Deformation Mechanism Expt
Novel experiments to populate model Expt/theory
Jointing methods Expt theory
Test structure Expt/theory Small scale
Structural monitoring Expt Numerical
Test structure Expt/theory Large scale
Design Assessment Construction Structure





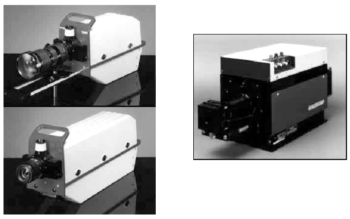
VISAR System



Imaging systems

- fast framing (68 frames) camera
- streak camera
- fast video (to 50 000 fps continuous)
- flash X-ray 4 channel; 300 kV
- Dark room
- Processing requirements
- X-ray high-speed camera development

High speed streak and framing



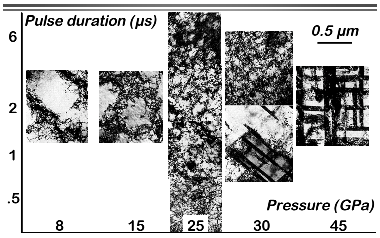
Consider the following scenarios

- Potential materials
  W, Ta, W26Re
- Rotating toroid
- Irradiation of a Ta Cylinder
  uniform beam profile
- Irradiation of a Ta Cylinder
  parabolic beam profile
- Tungsten cylinder around Ta core
- Hg or Ta jet

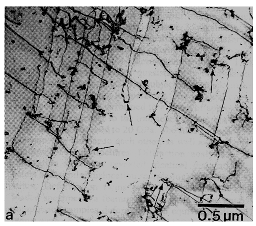
Pressure and pulse duration

- Both lead to
  higher dislocation density
  greater stored energy
  increased yield stress
  increased hardness
- Higher pressure leads to
  smaller dislocation cell size
  more twins, vacancies etc.
- Pulse duration effects saturate
  for Cu, 5 GPa for 2 μs + 10 GPa for 1 μs

Pulse and pressure effects in Ni



Tantalum Shocked to 7 GPa



Tantalum

- Deformation accommodated by long straight dislocations
- No evidence of shock hardening
- Defect generation and storage effected by high lattice friction (Peierl's) stress
  - *Early stages depend of motion of dislocations already present rather than generation*

Constitutive relations

- The equation of state is a constitutive equation for which the initial and final states are in thermodynamic equilibrium and there are *no* rate dependent variables
- A constitutive equation relates the initial to the final state of a material undergoing shock compression or high-rate deformation
- It is rate dependent and combined with the jump relations yields the Hugoniot curve

Grüneisen equation

- Vibrational energy contribution
- Strength effects small
- Material single homogeneous phase
- Consider solid as ensemble of coupled harmonic oscillators
- Use statistical mechanics to derive energy
- Express pressure as function of volume

Constitutive laws

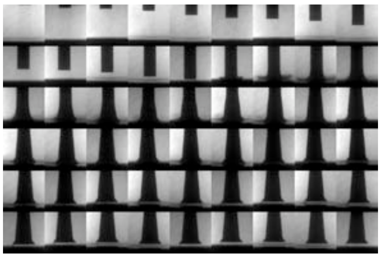
- Yield stress (*Y*) increases with strain rate
- Increase of *Y* with $\dot{\varepsilon}$ is more marked at low T
- *Y* up as grain size (*a*) down (Hall-Petch)

$$\sigma = \frac{k}{\sqrt{a}}$$

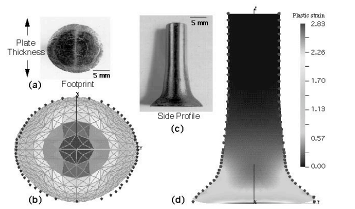
- Work hardening represented by

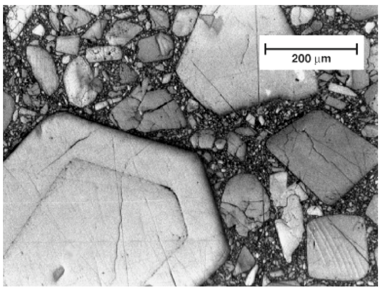
$$\sigma = \sigma_0 + k\,\varepsilon^n$$

Copper cylinder on rigid surface



Ta MTS model





High strain rate issues

- There are two components to consider in the stress state induced
  - Hydrostatic (pressure)
  - Deviatoric (strength)
- Two terms are interrelated
- Strength behaviour controlled by materials response under load

Principal operating mechanisms

- Irradiation leading to instantaneous T rise
  - *If whole bulk irradiated then*
  - *Pressure in central core of cylinder released by waves propagating in from free outer surface*
  - *If only part of target irradiated then*
  - *Compression front travels through heated region and interacts with free surfaces*
- These two scenarios require high strain rate models to describe response of materia
- Finally, creep may be significant if Ta not confined radially by magnetic field

Material Response

- Diffusion will be high which favours grain growth
- This will reduce strength and make it more vulnerable to failure
- Creep is favoured in BCC materials but larger grains with fewer grain boundaries increase creep resistence

Material Response

- Ta will deform by generation/annihalation of dislocations
- Twin formation can be ignored at this T
- Ta will anneal after loading
  - *But by how much?*
- If not completely annealed, recrystallization is favoured
- If this is case grain size is small leading to increased strength but lowered creep resistance

Material Response

- Conclusions
  - *Two mechanisms;*
    - *recrystallization and grain growth*
- They have opposing consequences
- Which dominates is not clear
- Effects of creep may be mediated by magnetic constraint?

Operational scenarios

- Potential materials
  - *W, Ta, W26Re*
- Rotating toroid
- Irradiation of a Ta Cylinder
  - *uniform beam profile*
- Irradiation of a Ta Cylinder
  - *parabolic beam profile*
- Tungsten cylinder around Ta core
- Hg or Ta jet

Rotating toroid

- Will contain region of hydrostatic compression with release waves entering
- Two propagating compression (shock) waves which will interact at opposite side of perimeter
- Possible high rate concerns
  - *Failure in tension at toroid axis*
  - *Yield as compression fronts interact*

Irradiation of a Ta Cylinder

- *Uniform beam profile*
- Hydrostatic pressure field results from instantaneous heating of cylinder
- Propagating release front radially and axially
- Possible high rate concerns
  - Failure in tension at toroid axis

Irradiation of a Ta Cylinder parabolic beam profile

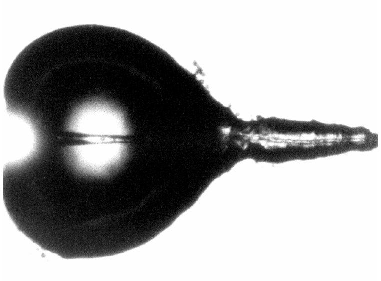
- Inhomogeneous heating allows cooler outer region
- Central high T, high P region
- Propagating release front radially and axially
- Confinement and inhomogenous field lowers strain rate, disperses pulse, reduces magnitude of tensile interactions

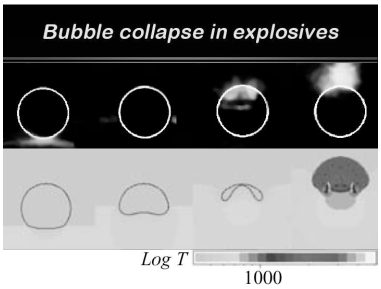
Tungsten cylinder around Ta core

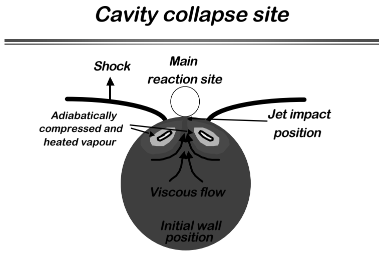
- Inhomogeneous heating allows cooler outer pipe of higher strength material
- Central high T, high P region, cooler high strength outer cylinder
- Propagating release fronts radially and axially again
- Confinement and inhomogenous field greater in this case and outer W is higher strength
- Disadvantage; Target is more complex to manufacture

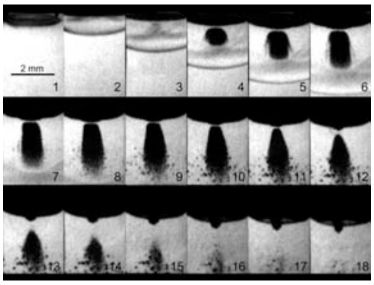
Interim Conclusions

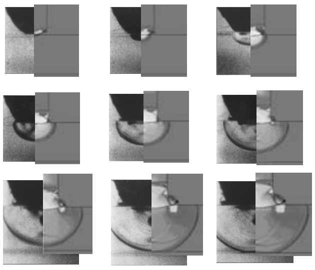
- T and P space in which the materials operate is not investigated for other phenomena/processes
- Materials mechanisms hypothesized but not defined
- Experimental techniques exist for high rate loading but not under these conditions
- Engineering experiment in beam vital
- Identifying operating mechanisms vital
- Operating mechanisms define necessary experiments
- Necessary experiments define necessary diagnostic developments

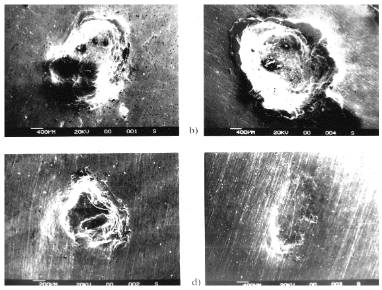


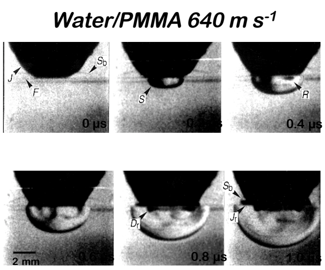

Bubble collapse in explosives
Log T
1000

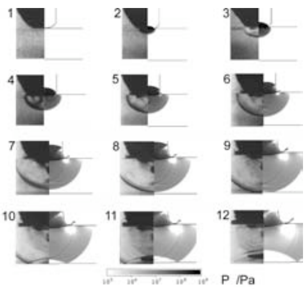

Cavity collapse site
Shock
Main reaction site
Adiabatically compressed and heated vapour
Jet impact position
Viscous flow
Initial wall position

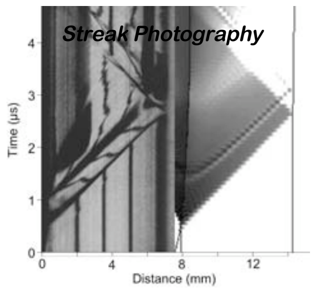

2 mm






Water/PMMA 640 m s-1
0 µs
0.4 µs
2 mm
0.8 µs


P /Pa


Streak Photography
Time (µs)
Distance (mm)