THE PHYSICS AND MECHANICS OF DYNAMIC SHEAR LOCALIZATION

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Technion (1912-1924)
Haifa (North of Israel)
Technion today...

17 Faculties
1 School of Medicine

About 13000 students

3 Nobel laureates
The Dynamic Fracture Laboratory (DFL)

Develop tools (experimental and numerical) to:

1. Investigate the thermomechanical response of materials subjected to high loading rate (constitutive testing, failure modes and mechanisms)

2. Investigate the response of cracks subjected to impact loading (dynamic fracture mechanics)

3. Structural health monitoring (end effects, AC electrical tomography)
Research themes

» Dynamic fracture mechanics
» Thermomechanics of dynamic flow and fracture
» Shear localization
» Dynamic and ballistic behavior of polymers
» Scaling of structural response to blast
» New experimental techniques. High triaxiality
» Dynamic testing of advanced ceramics: relation to microstructure.
» Wave propagation in gels and soft matter
» Structural health monitoring
» Electrical impedance tomography
» Scaling in dynamic fragmentation
» Numerical simulation of dynamic structural failure
» Biomechanics of dental implants (session BSSM)
Outline of the talk

- Statement of the problem
- On adiabatic shear: experiments (macroscale) and criterion
- Experiments (microscale) – thermomechanics - microstructure
- Modelling
- Conclusions
ADIABATIC SHEAR FAILURE

• Material / structural instability causing localization of the shear deformation into a narrow band when a material is subjected to dynamic loading (Tresca, 1879).

• Observed in many metals and polymeric materials (Bai and Dodd)
At the microscale.

ASB and crack x200

white etching ASB in 4340 steel x200

Artsi, Rittel and Roman, 1988
Plugging failure on the backside of an aluminum alloy armor plate (courtesy B. Dodd and F. Coghe)
In other words, the shear band is a local **heterogeneity** in an otherwise **homogeneous** neighborhood.
Adiabatic shear

Competition between strain-rate hardening and thermal softening (Zener-Hollomon, 1944)

Accepted criterion: critical failure strain
THE ROLE OF T

- Thermomechanical coupling causes a homogeneous temperature rise prior to localization
- Mechanical energy $\rightarrow$ Heat (PARTLY)

\[
\beta_{\text{diff}}(\varepsilon, \dot{\varepsilon}) = \frac{\rho C_p \dot{T}}{\dot{W}_p}
\]

\[
\beta_{\text{int}}(\varepsilon, \dot{\varepsilon}) = \beta = \frac{\rho C_p \Delta T}{W_p}
\]


RESULTS: Ti6Al4V – *Real time T monitoring*

NOTE THE MODEST ΔT PRIOR TO LOCALIZATION

Calculated assuming β=1
More on thermomechanical coupling
LH Zhang and S. Osovski

• TQ coefficient is **not a constant 0.9**
• Recorded temperature rise prior to localization remains quite modest (30-50 degrees)
• Dependence on the **deformation micromechanism** (twinning vs. slip)
• Thermal softening????
A NEW CRITERION FOR ASB

Quasi-static preload followed by dynamic tests

A NEW CRITERION FOR ASB

Quasi-static preload followed by dynamic tests

A

\( \epsilon_c \) failure ??
Dynamic energy vs. normalized static pre-ε

\[ W = \int_0^{\varepsilon_f} \sigma_{ij} d\varepsilon_{ij} \]

AM50
Interim Summary

- **Balance of dynamic energy:** \( W_M = W_T + W_S \)
  - **\( W_M \):** mechanical energy. Observed constant
  - **\( W_T \):** thermal energy. No significant role
  - **\( W_S \):** stored energy of cold work. Relevant
  - **\( W_S \):** emphasis on microstructural aspects and dynamic deformation only

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So, WHEN does localization start???

Central idea: Perform interrupted static and dynamic tests on a material (Ti6Al4V) that is prone to ASB shear localization, using the SCS specimen

F: fillet where ASB usually form
Interrupted tests

![Graph showing stress-strain relationship for static and dynamic interrupted tests.](image-url)
Quasi-static Ti6Al4V specimen - $\varepsilon=0.17$ not failed

(a) The typical microstructure consists of dislocation cells.
(b) Area showing stress-induced ($\alpha''$) martensite (arrowed) transformed from the $\beta$ phase, and its corresponding SADP.
Dynamically failed specimen $\varepsilon=0.24$

(a) Far from the ASB: Dislocation cells and stress-induced martensite. The typical SADP mainly contains misoriented $\alpha$ phase cells.

(b) Within the ASB: High dislocation density without any distinct morphology. The SADP shows incomplete rings indicating the presence of very fine recrystallized grains.

(c) Higher magnification of (b): The high dislocation density screens the fine grains revealed by the SADP.
Interrupted dynamic test – $\varepsilon_r=0.45$

Dynamically recrystallized grains (10-30 nm) formed in the highly dislocated area are indicated by arrows.

Free of dislocations. The corresponding SADP consists of ring patterns, typical of nanograined polycrystalline materials.

THIS SPECIMEN DID NOT FAIL!
An important observation (2008)

• Thorough TEM examination reveals a qualitatively identical microstructure for the interrupted and the fractured specimen.
• No new mechanism operates until failure
• One must therefore look for a quantitative evolution of the recrystallized phase. Difficult issue… Under progress

So, **HOW** does ASB progress? (2016)

0.9 failure strain. Micro cracks in ASB
TEM (FIB) specimens

[Diagram showing TEM (FIB) lamella and sample surface with labeled distances and features.]
The cracks are located in islands of DRX.

Dynamically recrystallized grains at the tip of a crack (box A).

The crack is perpendicular to the image. The crack tip location is indicated by the black arrow, at the mid-bottom of the image.

The dense DRX’ed region extends roughly **5 micron to each side**, with dashed lines delineating the extent of the DRX’ed region.
Sample between the cracks (box B): heavily deformed Ti matrix and small DRX’ed regions and highly deformed large grains (HDLG). A single DRX island is bounded by a white line. Corresponding diffraction patterns are inserted in the image.
(Box C), ~5 micron aside from the crack. Heavily deformed microstructure with a DRX island within it (marked by the white line), similar to the microstructure observed between the cracks (Box B). A twin is arrowed in the heavily deformed region.

Zooming: MD simulations

A quick peek at modelling results

Homogeneous distribution of stored energy (= DRX propensity)
Heterogeneous distribution of stored energy.

MORE REALISTIC

Is that all?

- Dislocation slip is important but not the only deformation micromechanism
- Twinning (shear) is also of prime relevance in low stacking fault energy (SFE) materials.....
- Ti-6Al-4V deforms by slip only (high SFE)
- Pure Ti deforms primarily by twinning and some slip (lower SFE)
Some micrographs – Pure Ti

Ti sample deformed to $\varepsilon = 0.9\varepsilon_f$, showing twins. No DRX found below that strain!
Same material at same strain. Different location. DRX is obvious

Either slip OR twinning.

But twinning **does not store energy**…..
• **Twinning** must not be overlooked!
• Twinning **dissipates energy**, thus delaying or precluding DRX.
• The coalescence of DRX islands with large local strain-rates leads to final failure (percolation?).
• Modeling (including microstructural evolutions.)
Going MACRO: Numerical implementation

25[mm] RHA plate

Trimmed 20[mm] FSP

- RHA steel -38[Rc] hardness
- $\sigma_y=1500$[MPa]

$W_c = 450$[MPa]  $W_f = 1350$[MPa]

- Rate sensitive tensile failure criterion

- 4340 steel -30[Rc] hardness
- Material constitutive behavior - JC$^1$

Axi-symmetric simulation
Used mesh – element size 0.6[mm]
Initial condition of velocity
## Experiments: RHA plate penetration

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Measured impact velocity ±20[m/s]</th>
<th>Depth of penetration or (P) perforation ±0.05[mm]</th>
<th>FSP weight ±0.01[gr]</th>
<th>FSP length ±0.02[mm]</th>
<th>Inner crater diameter ±0.05[mm]</th>
<th>Outer crater diameter ±0.05[mm]</th>
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<tr>
<td>9</td>
<td>1151</td>
<td>11.05</td>
<td>46.79</td>
<td>20.32</td>
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<td>6</td>
<td>1248</td>
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<td>38.45-39.10</td>
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<tr>
<td>8</td>
<td>1394</td>
<td>P</td>
<td>46.51</td>
<td>20.58</td>
<td>39.85-41.70</td>
<td>21.35-26.90</td>
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<tr>
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<td>1460</td>
<td>P</td>
<td>46.60</td>
<td>20.95</td>
<td>41.70-42.50</td>
<td>23.60-26.70</td>
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<tr>
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<td>P</td>
<td>46.36</td>
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<td>2</td>
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<td>P</td>
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<td>48.35-49.60</td>
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<td>P</td>
<td>46.74</td>
<td>20.68</td>
<td>49.20-54.05</td>
<td>28.95-30.45</td>
</tr>
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</table>

Local stress-strain curve of damaged material for strain energy density criterion

Strain criterion
\[ \sigma^*_{eq} = 1000 \text{ [MPa]} \]
\[ D = \begin{cases} 0 & \varepsilon \leq \varepsilon_{cr} \\ \frac{\varepsilon - \varepsilon_{cr}}{\varepsilon_f - \varepsilon_{cr}} & \varepsilon \geq \varepsilon_{cr} \end{cases} \]
\[ \varepsilon_{cr} = 0.5 \]
\[ \varepsilon_f = 1.5 \]

PSED criterion
\[ \sigma^*_{eq} = 1000 \text{ [MPa]} \]
\[ D = \begin{cases} 0 & W \leq W_{cr} \\ \frac{W - W_{cr}}{W_f - W_{cr}} & W \geq W_{cr} \end{cases} \]
\[ W_{cr} = 500 \text{ [MPa]} \]
\[ W_f = 1500 \text{ [MPa]} \]

\[ \sigma = \sigma^* \left(1 - D^b \right) \]

Parameters are determined experimentally

- Very high strains can be achieved
- Simplified material model

"Shear band toughness"
# Comparison of impact velocity 1150 [m/s]

<table>
<thead>
<tr>
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<th>Experiment</th>
<th>Simulation</th>
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<tr>
<td>Impact velocity</td>
<td>$1151 \pm 20$ [m/s]</td>
<td>$1150$ [m/s]</td>
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<tr>
<td>DOP</td>
<td>$11.05 \pm 0.1$ [mm]</td>
<td>$11.1$ [mm]</td>
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<tr>
<td>Crater diameter</td>
<td>$36.3 - 37.4 \pm 0.1$ [mm]</td>
<td>$37.34$ [mm]</td>
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<tr>
<td>Bulge length</td>
<td>$4.97 \pm 0.1$ [mm]</td>
<td>$5.04$ [mm]</td>
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</table>

![Comparison of impact velocity 1150 [m/s]](image)

- Penetration crater
- Plate’s rear side
Comparison of impact velocity 1400[m/s]

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Simulation</th>
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<tr>
<td>Impact velocity</td>
<td>1394±20[m/s]</td>
<td>1400[m/s]</td>
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<td>Crater maximal diameter</td>
<td>39.45-40.7±0.1[mm]</td>
<td>39.53[mm]</td>
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<td>Plug exit velocity</td>
<td>196±20[m/s]</td>
<td>180±20[m/s]</td>
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<td>Plug diameter</td>
<td>20.9-26.2±0.1[mm]</td>
<td>26.05[mm]</td>
</tr>
<tr>
<td>Plug height</td>
<td>22.2±0.1[mm]</td>
<td>20.1[mm]</td>
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</table>

~160[µs] after impact

~440[µs] after impact

Plate’s front side

plug
### Comparison of impact velocity 1900[m/s]

<table>
<thead>
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<th>Simulation</th>
</tr>
</thead>
<tbody>
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<td>Impact velocity</td>
<td>1920±20[m/s]</td>
<td>1900[m/s]</td>
</tr>
<tr>
<td>Crater maximal diameter</td>
<td>49.20-54.05±0.05[mm]</td>
<td>49.24[mm]</td>
</tr>
<tr>
<td>Crater minimal diameter</td>
<td>28.95-30.45±0.05[mm]</td>
<td>28.99[mm]</td>
</tr>
<tr>
<td>Fastest fragment velocity</td>
<td>723±20[m/s]</td>
<td>700±10[m/s]</td>
</tr>
</tbody>
</table>

Conclusions

• Adiabatic shear has microstructural origins.
• DRX evolution and kinetics must be further studied and modeled, taking twinning into account.
• DRX is driven by stored strain energy (microstructure).
• Macro-modeling can be based on a strain energy density + damage criterion.
Thank you for your attention.