Damages and Matter ejection during HVI on brittle structures: Implications for Space Environment

Presented by:

Yann MICHEL\textsuperscript{(1,2,3)}
PhD CEA-CESTA / CNES / ENSICA

N. Le Roux\textsuperscript{(1,3)}, C. Durin\textsuperscript{(1)}, C. Espinosa\textsuperscript{(3)}, A. Moussi\textsuperscript{(1,4)}, J-M. Chevalier\textsuperscript{(2)}, J-J. Barrau\textsuperscript{(5)}

Affiliations:
\begin{itemize}
  \item \textsuperscript{(1)} CNES, Toulouse
  \item \textsuperscript{(2)} CEA-CESTA, Le Barp
  \item \textsuperscript{(3)} ENSICA, Toulouse
  \item \textsuperscript{(4)} ONERA/DESP
  \item \textsuperscript{(5)} Université Paul Sabatier, Toulouse
\end{itemize}
1. INTRODUCTION

2. Analysis impacted thin brittle targets: DDS & HST-CS

3. Experimental Characterisation of ejected matter
   *Fragments collection and high speed videos*

4. Mechanical analysis of damages and SPH numerical simulations:
   *Simple thin SiO2 targets vs. Multilayered HST solar cells*

5. CONCLUSIONS & PROSPECTS
INTRODUCTION: Brittle materials & SD population

- **Growth suspicion of Space Debris population**
  - Self generation processes (ejectas and spalls)
  - Results from Hubble solar array post-flight analysis
  (Moussi et al, 2005) => Role of Secondary debris?

- **Brittle materials behaviour under impact**
  - Size of damages / Projectile’s diameter
  - Permanent densification / Spallation – big spalls
  - Ejected Mass / Impacting Mass > 100

- **Use of brittle materials for Space Platforms**
  - Optics
  - Major constituents of cells used for Solar arrays
    - Protecting glass layers
    - Cell’s materials
  - Very Large area exposed to SD environment

⇒ Sensitivity of brittle materials to HVI added to their use for large solar panels exposed to the space environment might make them a non-negligible Space Debris secondary source
**Experimental facilities & Impacted targets**

- **Thin brittle Targets**
  - **Disposable Debris Shield, DDS (CEA)**
    - 1.1 or 2mm Borofloat plates
    - Role: Protection of 10mm Main Debris Shield from shrapnels resulting from Laser MegaJoule target disassembly
  - **Hubble Space Telescope Solar Cells, HST-CS (CNES/ONERA, ESA)**
    - 0.7mm multilayered structure
    - Front-back & Front-top impacts

- **Experimental facilities and Analysis procedure**
  - **MICA double stage light gas gun (CEA)**
    - Projectiles: Φ < 2mm
    - Velocities: 800 – 4500 m/s
    - *This study:* D=500μm Steel Spheres
  - Analysis procedure
    - Confocal & SEM microscopy
    - Perhometer to compute ejected volume
    - Coating and cutting
• 2mm Disposable Debris Shield, DDS (CEA)
  ‣ Similar Damages for both faces:
    – Perforation hole or central pit
    – Shattered zone / fractured zone
    – Wide spallation zone / Radial cracks
  ‣ Shielding performances:
    – Ballistic Limit: V ~ 1500 m/s
    – Spallation Limit: V ~ 1250 m/s

• Hubble Space Telescope Solar Cells, HST-CS (CNES/ONERA, ESA)
  ‣ Impacts generating damages on the cover glass side of the solar cell
  ‣ Front-Top morphologies
    – Central pit with compacted cover glass
    – Wide spallation zone
  ‣ Front-back morphologies
    – No damages in the substrate
    – Wide spallation zone in the cover glass and/or the silicon layer
Ejected Volumes measurements

- **2mm Disposable Debris Shield: Importance of rear spallation**

<table>
<thead>
<tr>
<th>Impact velocity</th>
<th>1350 m/s</th>
<th>1900 m/s</th>
<th>2200 m/s</th>
<th>3010 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ejected mass</td>
<td>48.8 mg (No-Perf)</td>
<td>73.1 mg (Perf)</td>
<td>95.3 mg (Perf)</td>
<td>122 mg (Perf)</td>
</tr>
<tr>
<td>% ejected mass due to rear spallation</td>
<td>68 %</td>
<td>59 %</td>
<td>72 %</td>
<td>82 %</td>
</tr>
<tr>
<td>Mass Ratio</td>
<td>95.6</td>
<td>143.3</td>
<td>186.8</td>
<td>239.1</td>
</tr>
<tr>
<td>Volume ratio</td>
<td>338</td>
<td>507</td>
<td>660</td>
<td>845</td>
</tr>
</tbody>
</table>

- **HST-CS Front-Top & Front-Back craters**

Total number of major craters on Hubble solar arrays:

⇒ 494 FT / 508 FB
⇒ VEjected ~ 0.1043 x Dco^2.5

Total ejected volume for 5 year Exposure = ~ 1530 mm³

89% due to Front-back impacts

Corresponding number of D=50µm Spheres = 20,000,000 objects !!!
Passive collection of ejected fragments

• Experimental setups
  ‣ Paperboards coated with adhesives
  ‣ Aerogel collectors
  ‣ Location: ~ 10cm behind an impacted target

• Collected fragments clouds
  ‣ HST solar cell impacted at $V = 2.89$ km/s (a)
  ‣ 2mm DDS impacted at 3 km/s (b)
• Fragments generated behind an HST-CS (100mm² collector)
  ‣ Collector perforated by Projectile (fragmentation?)
  ‣ **6 major spalls** (Typical size > 300µm) & **70 spalls** (Typical size > 150µm)

• Fragments origin – Spectrometer analysis (Mapping mode)
  ‣ Silicon fragments
    • Numerous
    • Small fragments (<70µm)
  ‣ Glass spalls
    • Big spalls (>100µm)
    • 1 huge spall (3 x 1.5 x 0.15mm)
    • Remnant layer of silicon on many glass spalls
• Shot 52-05 and 55-05 – MICA Launcher – Video ~12μs / frame

  - **Target:** 1.1mm Disposable Debris Shield (Borofloat glass)
  - **Projectile:** Steel Sphere, \( \Phi = 500\mu m \)

  - **Ejection phenomenology:**
    - Impact \( \rightarrow 30\mu s \): High velocity jets – \( V \sim 1000 \text{ m/s} \)
    - 50\( \mu s \) \( \rightarrow 1\text{ms} \): Spalls clouds expansion – \( V \sim 40 - 150 \text{ m/s} \)
    - Incident impacts: Same ejection processes with \( \neq \) ejection angles

Shot 52-05 – \( V \sim 3000\text{m/s} \) – \( \alpha = 0^\circ \)

Shot 55-05 – \( V = 3140\text{m/s} \) – \( \alpha = 15^\circ \)
• Shot 56-05 – MICA Launcher – Video (0→1ms; ~12μs / frame)
  ‣ **Target**: 0.7mm Hubble’s solar cell – Front-back impact
  ‣ **Projectile**: Steel Sphere, Φ = 500μm - Velocity = 2890 m/s
  ‣ **Ejection phenomenology**:
    – Impact → 30μs: High velocity jets – V~900m/s
    – 30μs → 1ms: Spalls clouds expansion – V~100m/s

⇒ **Similar ejection velocities / DDS**
⇒ **Less spalls (thinner target)**
⇒ **Unorganised spalls clouds**
• Spalls clouds analysis
  - Size, velocity and ejection angle measurement of representative spalls
  - No considerations on spalls number
  - Principal characteristics of ejected spalls
    - Size: 100µm to 1.1mm (maximal dimension)
    - Velocity: 0 – 100m/s
    - Ejection angle / impact axis: +/- 20°
    - DDS / HST-CS: unorganised spalls clouds for HST-CS, no clear size’s distribution)
Shock Response of brittle structures

- **Dynamic behaviour of glasses under intense shock loadings & Material Modelling**
  - Compressive behaviour – Modified JH-2 material model
    - Elastic behaviour under HEL (Hugoniot Elastic Limit)
    - Fragmentation and densification above HEL
      - Isotropic damage above HEL for compressive fragmentation
      - Polynomial EOS with permanent densification effects for compression and releases
  - Tensile behaviour – Tensile failure criterion
    - Principal stress criteria with tensile deactivation of SPH particles
  - Material model Validation
    - Compressive behaviour validated for Explosives testing & flyer plates impacts P → 35GPa (CEA-CESTA)
    - Ability to model 1D spallation
    - Validation for Fused Silica and Pyrex Glass

- **Shock propagation in a multilayered structure: application to solar cells**
  - Role of involved material
  - 3 layers simplification: Substrate (composite + adhesive) / Semiconductor (Silicon) / CMX cover glass
    ⇒ Tensile loadings due to rarefaction waves propagating into HST-CS coming from:
      - CMX coverglass free surface
      - Si/CMX interface
    ⇒ High pressure levels reached into Silicon layer due to its high shock impedance
  - Role of adhesives layers?
• **Mesh, boundary conditions and material model**
  - 2 mm DDS (210.000 particles) – Modified JH-2 material model (Fused silica data set)
  - Steel Spherical projectile (544 particles) – Steinberg-Guinan material model + Mie-Gruneisen EOS
  - Normal impacts with 2 symmetry planes
  - Velocity range: 800 to 4000 m/s

• **Damages & Shielding performances**
  - Ballistic limit (1500 m/s) & spallation limit (1250 m/s)
  - Spalled diameters (err% < 12% until ballistic limit)

• **Prediction capabilities for matter ejection**
  - High velocity clouds of deactivated particles
  - Clusters of active particles

**Images:**
- DDS rear side: V = 1655 m/s, V = 1256 m/s, V = 1599 m/s
- 2mm DDS SPH calculation: V = 1250 m/s, SPALLATION LIMIT
- 2mm DDS SPH calculation: V = 1500 m/s, BALISTIC LIMIT
- 2mm DDS - t = 50µs, V = 3000 m/s
• 2D SPH calculations
  ‣ Analysis of stacking effects on potential spallation effects
  ‣ 150µm Al projectile, V = 1000m/s, HST 3 layers (Si & CMX modelled with JH-2-HVI)

⇒ Silicon & cover glass layers are submitted to intense tensile loadings
⇒ Bigger spalls in the cover glass

Note: Necessity to identify the behaviour of Silicon under intense shock loadings...

• Preliminary 3D SPH calculations
  ‣ 700µm 3 layers solar cell (Al / Si / SiO2)
  ‣ Model: 185,000 particles
  ‣ D=300µm Spherical Aluminium Projectile
  ‣ Velocity range: 500 to 4000m/s

⇒ Ability to reproduce class C morphologies with hole in substrate and spallation of Si and CMX layers
⇒ As for DDS, both high velocity jets and spalls have been reproduced
Conclusions & Prospects

• CONCLUSIONS
  ‣ Front-Back impacts causing spallation of cell’s brittle layers are the most damaging for the space environment: 90% of total ejected mass from HST arrays due to FB impacts
  ‣ Characterisation of ejected matter
    – Small Silicon fragments due to cell’s confinement
    – Bigger glass spalls due to spallation phenomenon of the protecting glass
  ‣ Meshless numerical methods coupled to adapted material models provide interesting results for simple brittle targets
    – Damages and Shielding performances of DDS + Ejection tendencies conform with experiment
    – Encouraging preliminary results for damages on 3 layers simplified Silicon cell

• FUTURE WORK
  ‣ Experimental study of solar cells new generation
    – Germanium vs silicon cells
    – Substrate (carbon/Honeycomb) and potential channelling of projectile residues
    – Sticking conditions
  ‣ Numerical simulations
    – 2D analysis of stacking and sticking effects on loading conditions seen by the target
    – Improvements of 3D SPH simulations of HVI on simplified solar cells structures
  ‣ Post collection analysis of aerogel collectors using 3D X-rays tomography
HVI on Brittle Structures: Implications for Space Environment

Any Questions?

E-mail: Yann.michel@ensica.fr