Time-Resolved Microscopic Imaging of Laser-Induced Material Modifications in Optical Materials

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Time-Resolved Microscopic Imaging of Laser-Induced Material Modifications in Optical Materials

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Motivation

• Materials science problem: localized energy deposition → sequence of transient material modifications and formation of a void
  – Energy coupling mechanisms
  – Solid state material response to localized extreme conditions
  – Energy transport through complex material phases
  – Material displacement and lattice transformation

• Practical reasons:
  – What causes and/or how to eliminate damage in optical components
  – How damage evolves (timeline)

Carr et al., APL, 89, 131901 (2006)
Objectives

• We want to elucidate the processes involved during a damage event in optical materials
  – Develop the experimental capabilities to measure the relevant processes with adequate resolution
  – Use experimental results to validate theoretical models

Today I will discuss the material response during the cooling phase in bulk fused silica following localized energy deposition via ns laser-induced breakdown
Time-resolved microscopy system is used to image the evolution of bulk damage in SiO₂

**Polarization Sensitive System Transmission Geometry**

- Adjustable time delay between pump and probe pulses to 100 ms
- Polarizing cube beam splitter
- 355-nm Pump
- ~3 ns FWHM
- Sample
- ~4.5 ns

**Static Image Resolution ~1 µm**

- PARALLEL POLARIZATION IMAGE maps index of refraction changes
- ORTHOGONAL POLARIZATION IMAGE maps stress via depolarization

- Direction of pump propagation
- Bulk damage site
- Stress field
- Filament out of focus

CMH4, Negres et al., 05/17/2010
Images at different delays reveal the material response during the entire timeline of bulk damage

1) Shock fronts  2) Initiation and propagation of cracks  
3) Transient absorption at crack and core regions  4) Return to solid phase

The spatial resolution of dynamic events was limited at the time by the pulse length of the probe pulse.
Images at different delays reveal the material response during the entire timeline of bulk damage.

1) Shock fronts  2) Initiation and propagation of cracks  
3) Transient absorption at crack and core regions  4) Return to solid phase

Early dynamics can be resolved using a 150-ps probe laser

Limited spatial resolution of dynamic events (5-ns probe pulse -> 30 µm resolution)

Modeling of ps-time resolved images of shock fronts, crack propagation and stress waves is currently underway (P. DeMange)
In the following, I will discuss the material response during the cooling phase.

1) Shock fronts
2) Initiation and propagation of cracks
3) Transient absorption at crack and core regions
4) Return to solid phase

- Results suggest that crack growth proceeds up to ~30 ns delay.
- At delays longer than ~50 ns, the transient overall dimensions of the damage site appear the same as the final.
- However, the contrast between the transient and final images (in the parallel polarization) is different.
Ratio TR (final/transient) images highlight the locations of the transient absorption

- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns
Ratio TR images highlight the locations of the transient absorption

- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns
- The core region is also associated with a transient absorption for a much longer time, up to ~ 200 μs

Image at 500 μsec delay suggest that transient absorption terminates
Ratio TR images highlight the locations of the transient absorption

- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns
- The core region is also associated with a transient absorption for a much longer time, up to ~ 150 μs
- We postulate that the material in the core region is in a liquid or vapor phase at high T

The last step in the damage process is returning of the “core” region to solid phase

Hypothesis: This phase change will lead to changes in the scattering properties of the material

Our imaging system can be re-configured to a back-scattering geometry (BS)

- This scattering effect may be due to microvoid formation by volume contraction during cooling of the material in liquid phase\(^3,4\)
- This effect terminates at about 70 msec delay

We use a pump and probe damage testing system to differentiate between the loss mechanisms.

The presence of enhanced absorption by the host material due to the pump will lead to higher energy deposition by the probe pulse.

This effect will be manifested as a larger in size damage site from the combined exposure to both pump and probe pulses.

Transient images revealed changes in the absorption and/or scattering of the probe laser light incident upon the damaged volume.

We indirectly monitor the transient absorption (not scattering) in the damaged region.
We compare the dynamic images of bulk damage with the pump-probe damage testing results\(^5\)

Combined results confirm the presence of transient absorption in the pump-induced modified material volume (cracks & “core” regions)

We extrapolate temperatures along the timeline based on the temporal behavior of the emission during a bulk damage event in SiO$_2$.

![Temperature vs. Delay Time Graph]

- Relevant T for SiO$_2$ (Corning):
  - glass transition @ 1310 K
  - softening point @ 1860 K
  - flows like honey (at room T) at ~2800 K (National Honey Board)

The return of the melted material to solid phase at ~70 ms (as suggested in BS images) and the estimated T are in excellent agreement with the softening point of SiO$_2$.

- The transformation of silica at high T to a more absorptive material phase has been previously suggested$^{7,8}$


We correlate previous observations to the microscopic structure of the bulk damage site.

- The core region is about 7 μm in diameter
  - contains a cavity (~3-4 μm in diameter)
  - the outer ring is homogeneous suggesting that it was formed at a later time

- Mechanically damaged region (due to the shockwave propagation following the initial energy deposition) was formed earlier (at times shorter than 50 ns) and extends out to ~100 μm
Conclusions

- We have developed an experimental system capable of imaging bulk damage evolution with adequate spatial and temporal resolution.
- The results reveal the salient behaviors associated with the material response during the cooling phase:
  - The mechanically damaged region is forming at times shorter than 50 ns.
  - A large population of defects is established in the cracked region and decays within 300 ns.
  - There is a core region that remains in a high temperature, liquid-gas state and exhibits a strong transient absorption for about 200 μs.
  - The material returns to solid phase at ~70 ms delay after laser energy deposition.
- Future work is aimed at:
  - Resolving the shockwave physical dimensions and early dynamics.
  - Formation dynamics and absorption characteristics of electronic excitation region.
  - Employ hydrodynamic codes to model experimental observations and develop reliable theoretical models for this intermediate physical regime between cold materials and HED matter.