Laser Ablation From Brittle Solids

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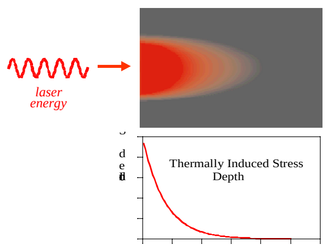
The mechanisms by which material ablates from brittle solids can lead to removal of far more material than would be expected considering only the total energy deposition. The optical, thermal, and mechanical properties of the material, together with the rate and mechanism of energy deposition, determine the material response.

In an absorptive material, the laser heats a small volume (several mm in diameter) in an otherwise cold material, leading to thermally induced stress. If the energy deposition rate is low compared to the thermal diffusion rate, the response is elastic, i.e. the material expands but does not ablate. Depositing the energy on a time scale at which thermal expansion cannot be accommodated by elastic deformation leads to ablation via a thermal shock mechanism: shear stress is induced by differential expansion, leading to cracking and spalling. If the substrate is an aggregate of inhomogeneous materials, such as concrete, the mechanism is enhanced by the fact that each phase has a different coefficient of thermal expansion.

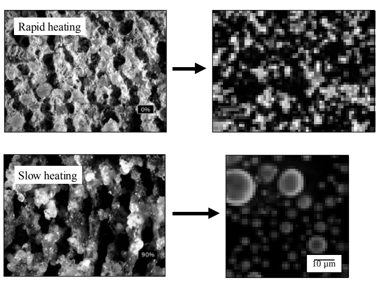
In a transparent substrate damage is dependent entirely on the development of damage networks after initiation at a chemical or physical defect. For example, fused silica with embedded 20 nm gold nanoparticles experiences severe damage when irradiated at high fluence, but only after several tens of laser pulses. The amount of energy deposited in such a small particle is insufficient in itself to cause bulk damage, however as the site is repeatedly irradiated, the physical nature of the defect changes and the substrate itself becomes absorptive. When the site reaches a threshold size, bulk damage occurs explosively. Again, the mechanism is differential thermal expansion on a fast time scale, but in this case ablation is dependent on the development of a damage network started at a localized initiation site. The role of nanoparticles in laser damage is thus demonstrated.

Absorptive substrate model:



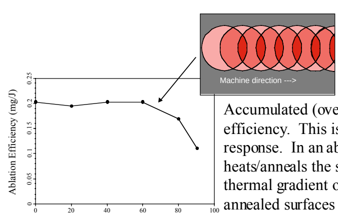
Material ablates across isotherms for which the induced stress exceeds the breaking stress.

System: Concrete ablated with 8 J Nd:YAG fundamental (1064 nm), 500 µs pulse, 1 mm spot



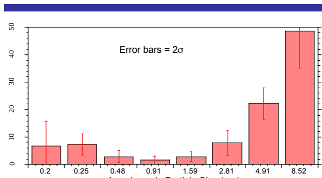
Material response:
Energy dissipation mechanisms in concrete

These photos show ablated concrete surfaces and ablation effluent. Thermal shock mechanism produces rough surface and fragmented effluent; melt/vaporization vitrifies the surface and produces aerosol particles.

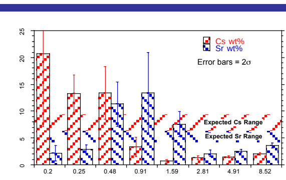


Laser pulse footprint on the surface

Accumulated (overlapping) pulses ***decrease*** ablation efficiency. This is the opposite of the transparent material response. In an absorptive material laser energy heats/anneals the substrate. Residual heat decreases the thermal gradient on subsequent pulses and produces smooth, annealed surfaces that reflect incident laser energy.

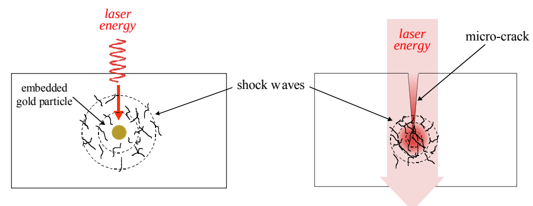


Bimodal distribution indicates two particle formation mechanisms, i.e. vaporization and melting



Cs and Sr are inhomogeneously distributed in the aerosol:
•Cesium collects in small particles : vaporization
•Strontium collects in intermediate particles : ?

Transparent substrate model:

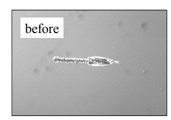


Embedded absorber can be ≤ 20 nm and still be effective

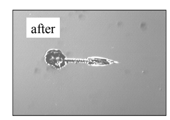
Pre-existing physical defects lead to crack network formation

System: High-quality fused silica ablated with 0.6 mJ Nd:YAG 3rd harmonic (355 nm), 7.6 ns pulse, 1 µm spot

Crater caused by embedded 20 nm gold particle



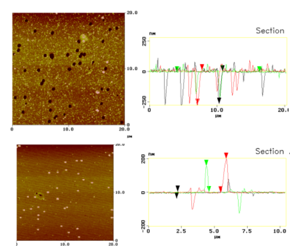
2 µm scratch before laser exposure



Damage after 30 shots at 1.2 x 10^9 W/cm^2

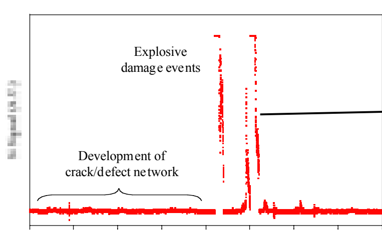
Material response:
Energy dissipation mechanisms in fused silica

AFM images and topographical analyses of fused silica samples with embedded defects after laser irradiation, showing the material response modes.

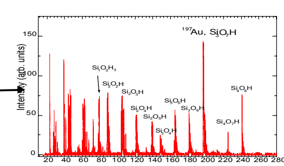


1.6 x 10^9 W/cm^2: Fast energy deposition leads to explosive cratering

0.7 x 10^9 W/cm^2: Slow deposition leads to inelastic deformation (blistering)



Accumulated pulses lead to explosive ablation. Embedded defects initiate micro-cracks which themselves concentrate laser energy and propagate. The explosion occurs when the crack network reaches the surface.



Mass spectrum of the damage event. Note the prominent gold peak caused by a 20 nm particle embedded 500 nm deep. With this method, we could detect particles much smaller than 20 nm.

Conclusions

- Energy deposition rate and material optical, thermal, and mechanical properties control material response to laser energy.
- In absorptive materials, fast deposition leads to ablation, slow deposition leads to melting and vitrification.
- In transparent materials, fast deposition leads to the initiation of a microscopic damage network that causes ablation only when it exceeds a certain size.
- Slow deposition can cause blistering, or can limit the damage to the immediate vicinity of the initiator.
- Material vaporization can lead to chemical segregation in ablation effluents.

Future directions:

- Extend absorptive materials work to natural, homogenous materials, such as granite.
- Investigate minimum defect size necessary to initiate damage in fused silica.
- Invesitage the effects of embedded nanoparticles such as ceria on fused silica damage thresholds.

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