Numerical Modeling of Heat Transfer and Damage Evolution due to HEL Irradiation

Dr. Joshua J. Radice
Dr. Peter J. Joyce
MIDN 1/C Andrew Tresansky
CAPT Joseph Watkins

Mechanical Engineering Department
United States Naval Academy

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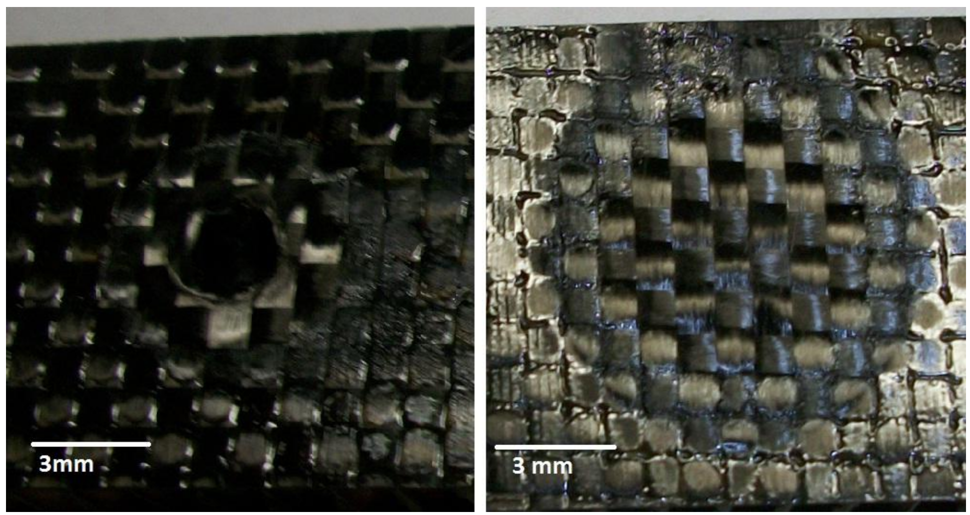
Overall Objective of Research Program

- Develop and validate predictive tools relevant to laser damage of materials.
- Capture laser drilled hole evolution.
- Capture radiative/transmissive damage to remainder of structure.



Puishys, J. Joyce, P. “Damage Tolerance of Laser Irradiated Composite Sandwich Structures.” USNA, 2011.

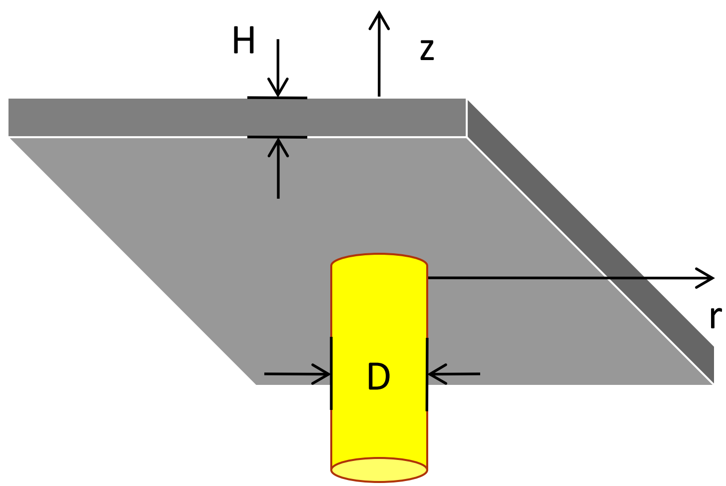
Current Thrust

- Develop a COMSOL Multiphysics simulation of damage and hole evolution for isotropic materials subjected to a 1070nm laser.

- Compare to experimentally observed laser damage evolution through a simple test material (PMMA).

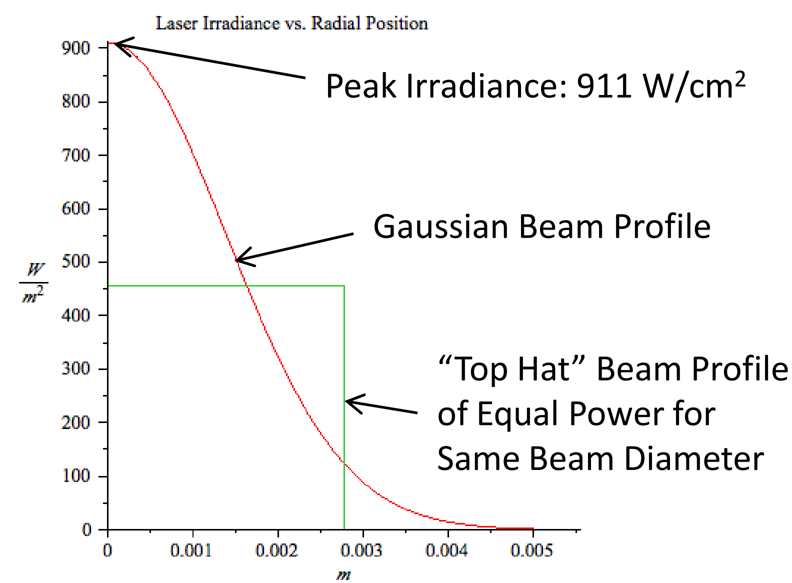
HEL Irradiation Problem and Laser Specification

- Finite Thickness Plate of Large Plan-view Area



$$I(r) = I_0 e^{-8\frac{r^2}{D^2}}$$

- DE Lab Laser Parameters:
  - IPG 1070nm Nd:YAG Laser.
  - Power: 110W (Measured)
  - Beam Diameter: 5.5mm (Per Mfg's Measurements)
  - $M^2 = 1.07$



Model Assumptions

- Laser modeled as a heat flux with a Gaussian radial distribution.

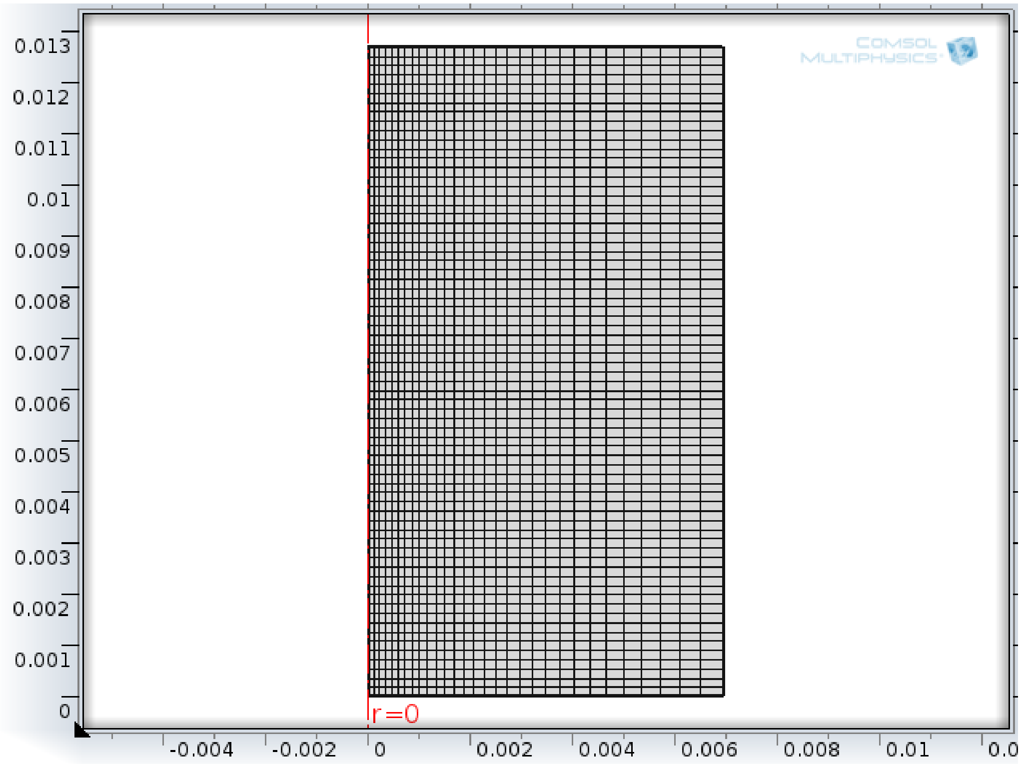
- 55% incident energy absorbed, 45% of incident energy reflected in accordance with published[1] Near-Infrared Reflective Spectroscopy (NIRS) measurements at 1070nm.

- Material changes phase directly from solid to vapor.

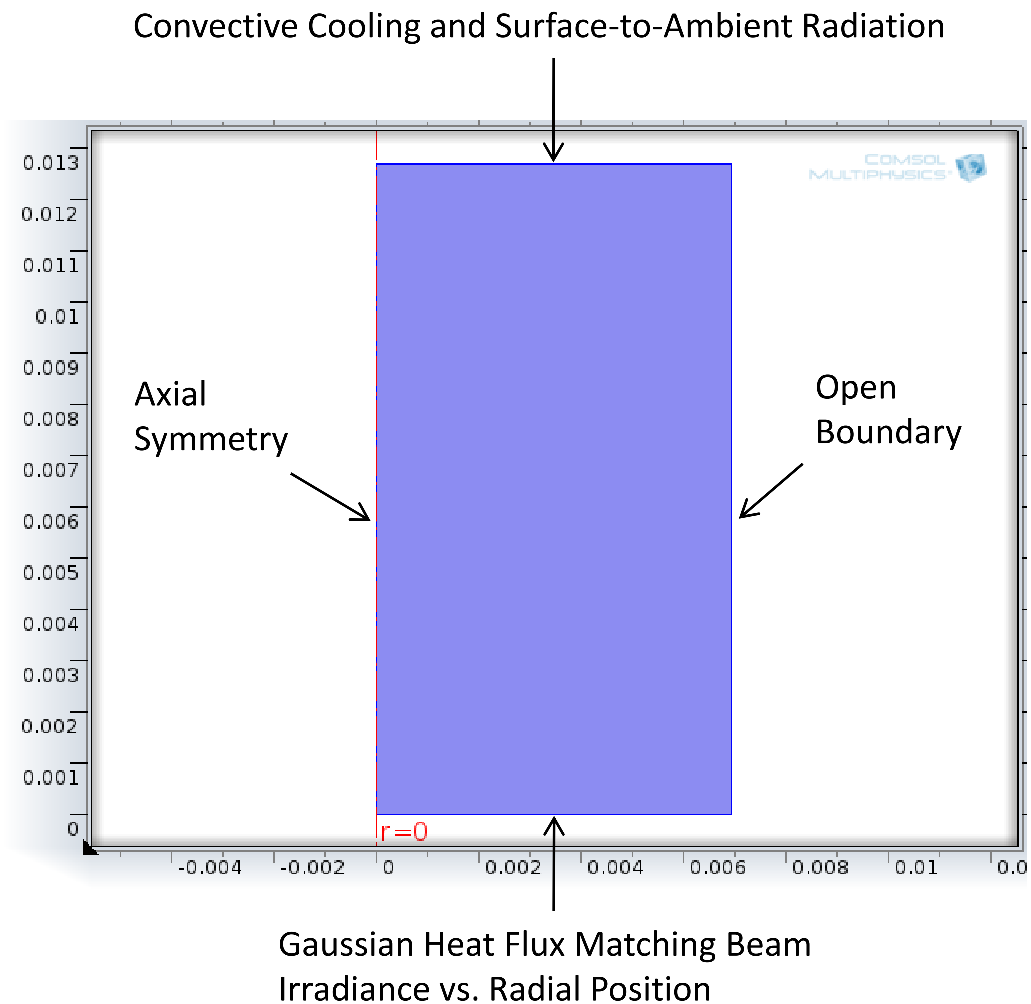
1: Lloyd, Christopher, "Ablation of Organic Polymeric Materials", Doctoral Dissertation, George Mason University

COMSOL Model: Domain and Element Model

- Axisymmetric model (only valid for isotropic materials)
- Mapped quad elements with higher fidelity near centerline



COMSOL Model: Boundary Conditions



Damage Evolution Strategy

- Specific Heat modified to include latent heat of vaporization over an experimentally determined temperature span.

$$C_p(T) = C_{ps} + d(T)\Delta_h$$

$$d(T) = \frac{d}{dT} h(T)$$

$$h(T) = (T - T_1)H(T - T_1)H(T_2 - T) + H(T - T_2)$$

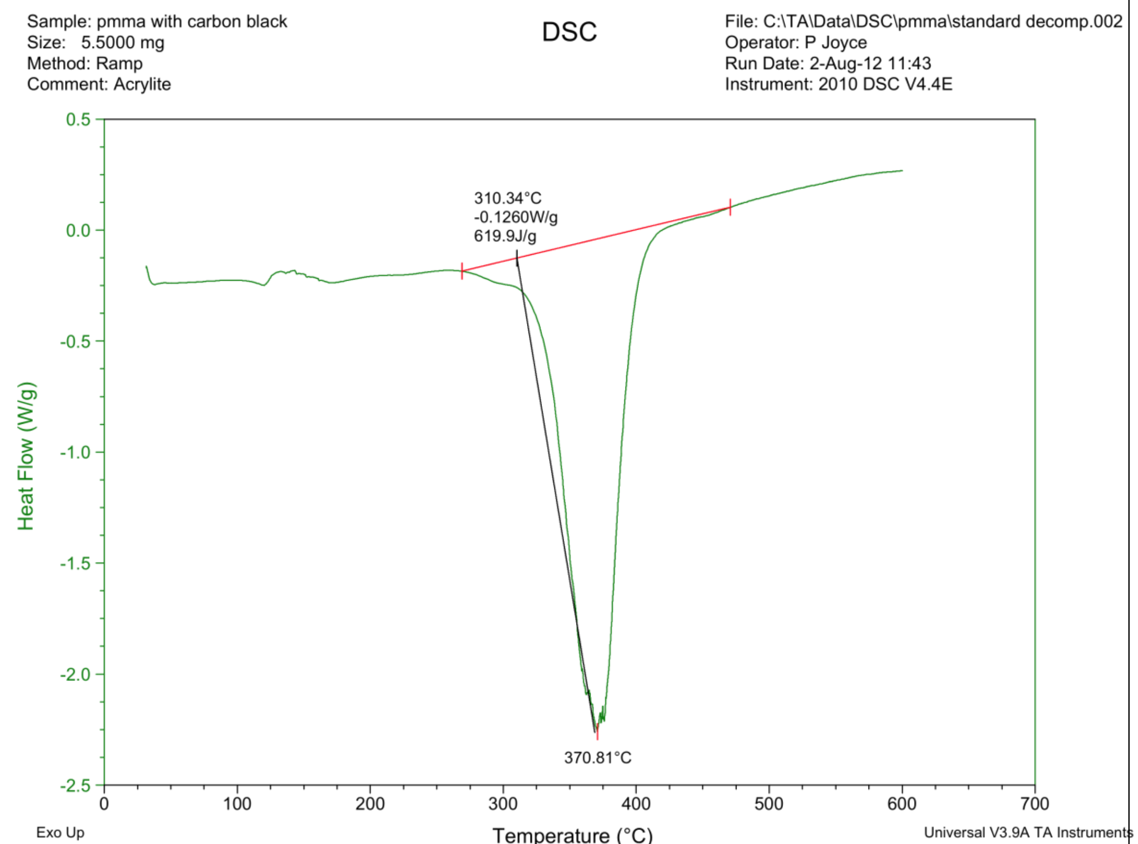
- Other Material properties artificially modified after vaporization.
  - Density and specific heats become that of air/vaporous material.
  - Thermal conductivity becomes "extremely large" in beam direction.
  - Thermal conductivity becomes "extremely small" in radial direction

Model Parameters (Part 1): Thermal Properties and Geometry

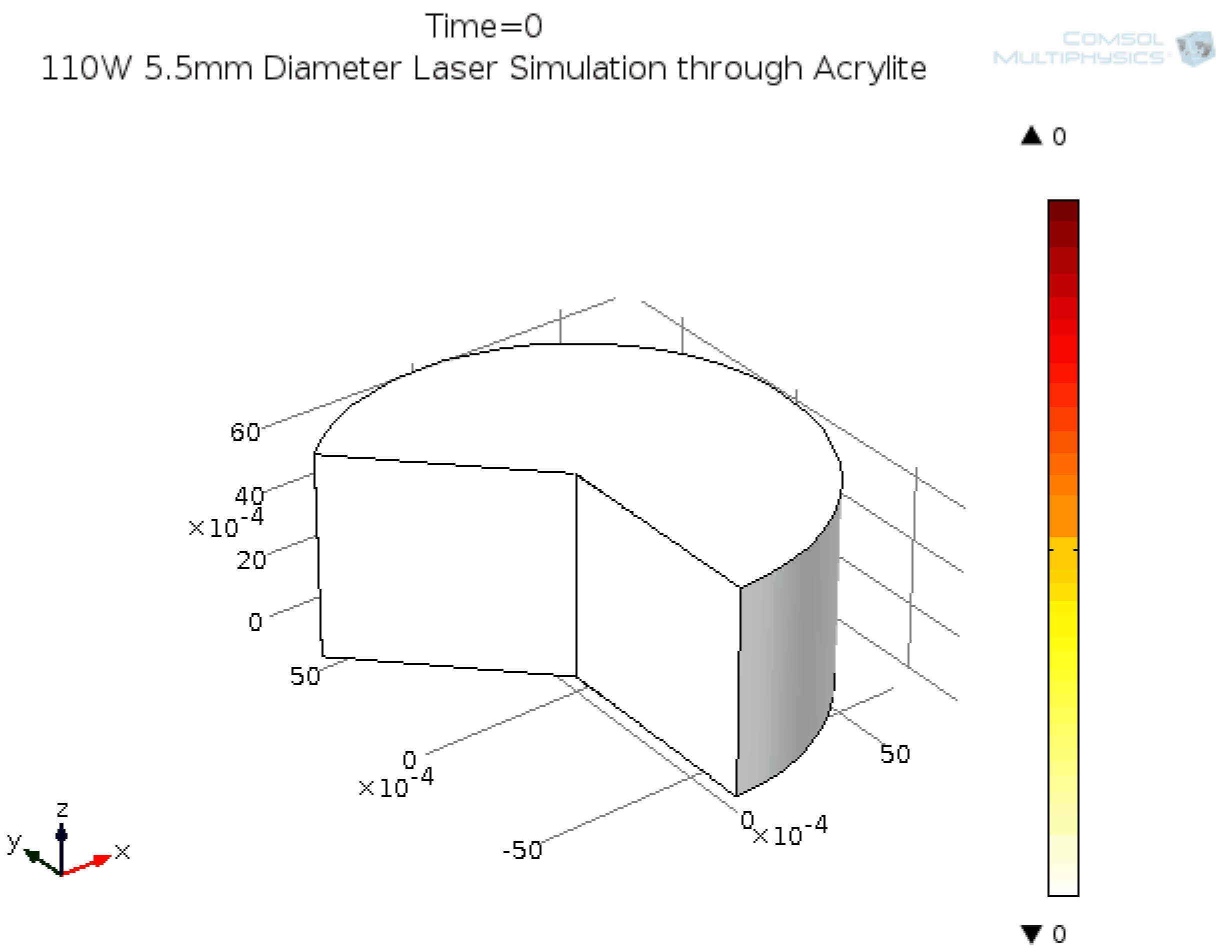
- PMMA Properties:
  - Density (ρ): 1190 kg/m^3
  - Thermal Conductivity (k): 0.19 W/m^2-K
  - Specific Heat (C_{ps}): 1470 J/kg-K
- Air/PMMA Vapor Properties:
  - Density (ρ): 1 kg/m^3
  - Specific Heat (C_{pv}): 1000 J/kg-K
- Boundary Heat Transfer Coefficients
  - Convection Coefficient (h): 25 W/m^2-K
  - Radiation Emmissivity Coefficient (ε): 0.85
- Thickness (H): 0.25in.

Model Parameters (Part 2): DSC Plot and the Latent Heat of Vaporization

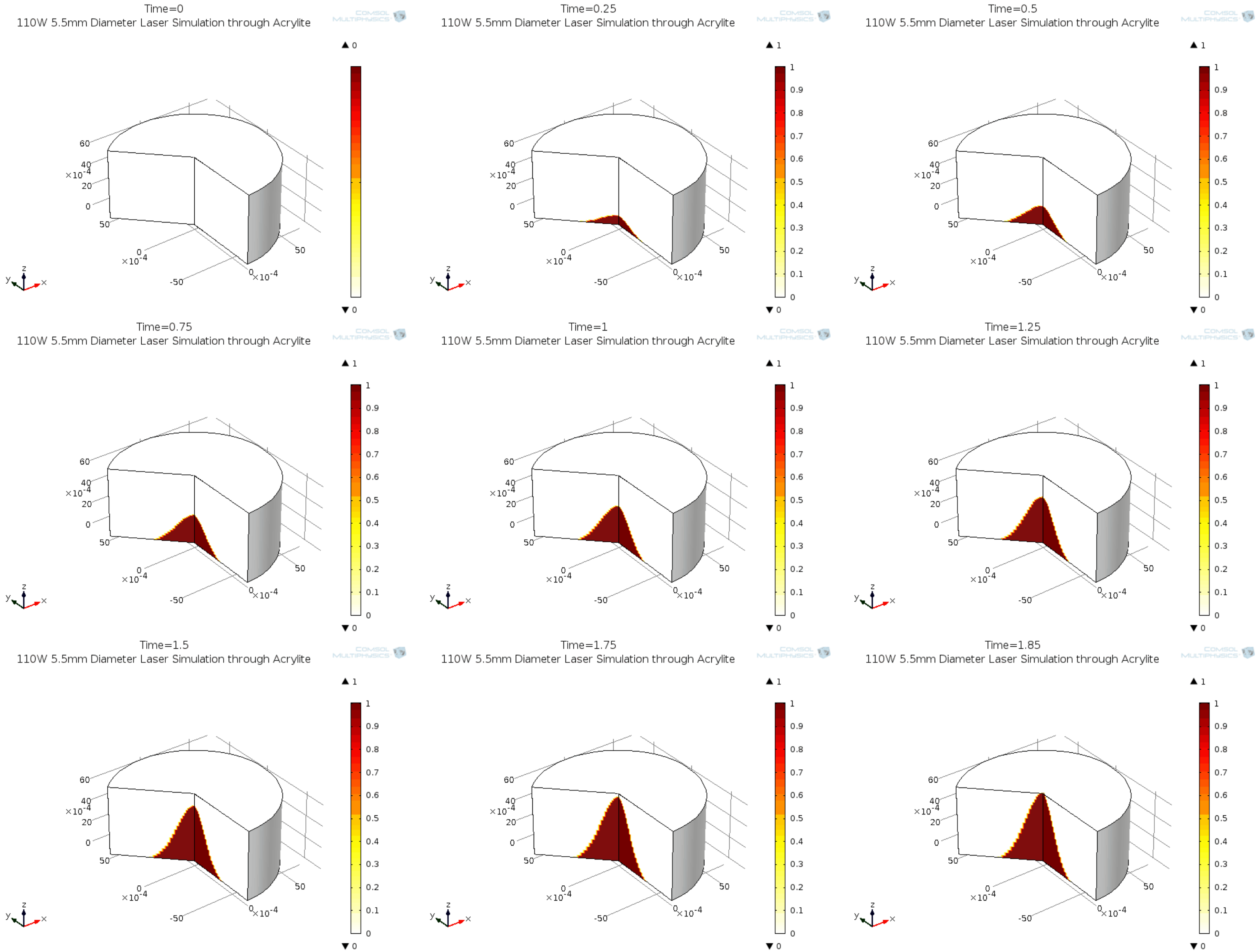
- Starting Vaporization Temperature (T_1): 310° C
- Ending Vaporization Temperature (T_2): 420° C
- Latent Heat of Vaporization (ΔH): 619.9 kJ/kg



Simulation Results (Part 1): Qualitative Evolution of Damage

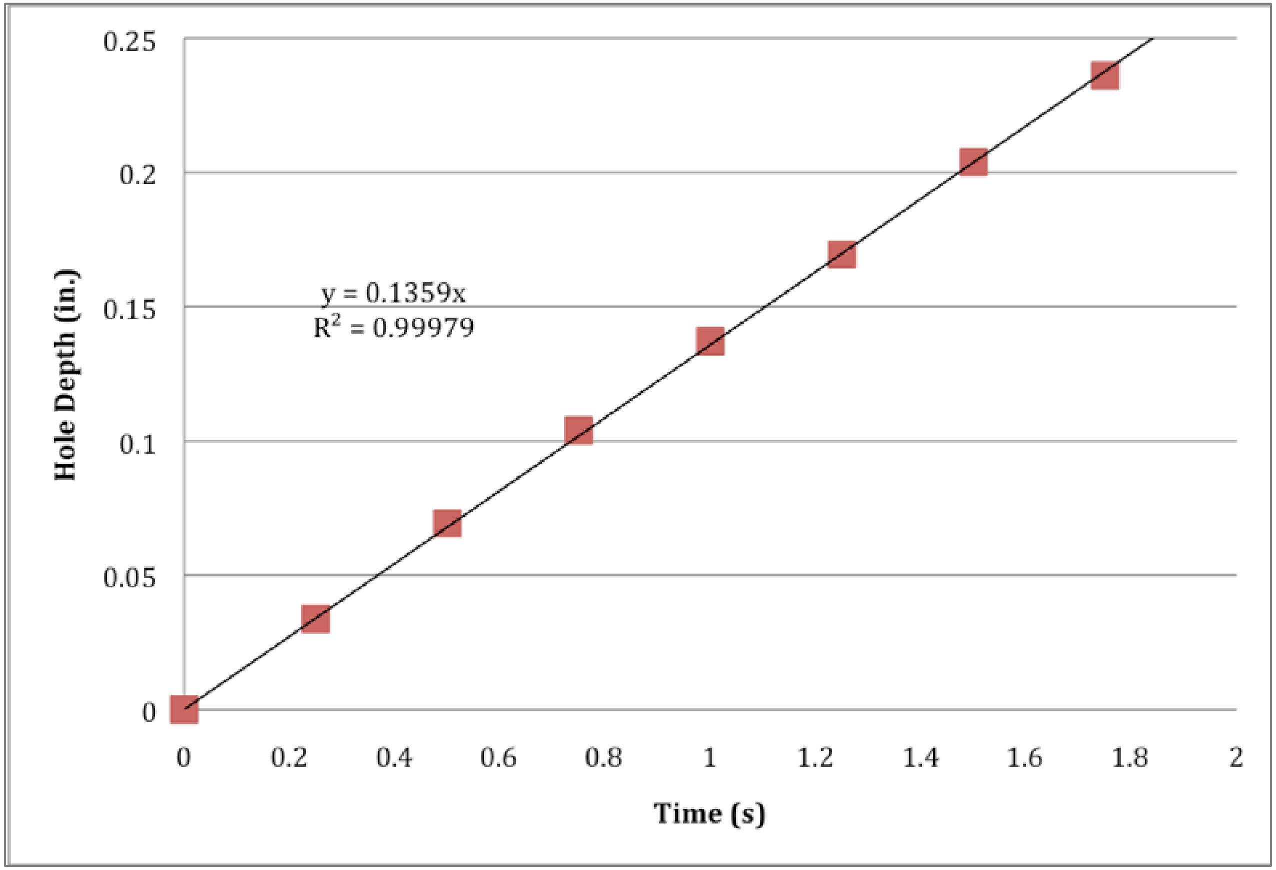


Simulation Results Backup:



Simulation Results (Part 2): Quantitative Evolution of Damage

- Largest Predicted Hole Diameter (Front Surface): 0.291 in.
- Hole Evolution Rate: 0.136 in/s.

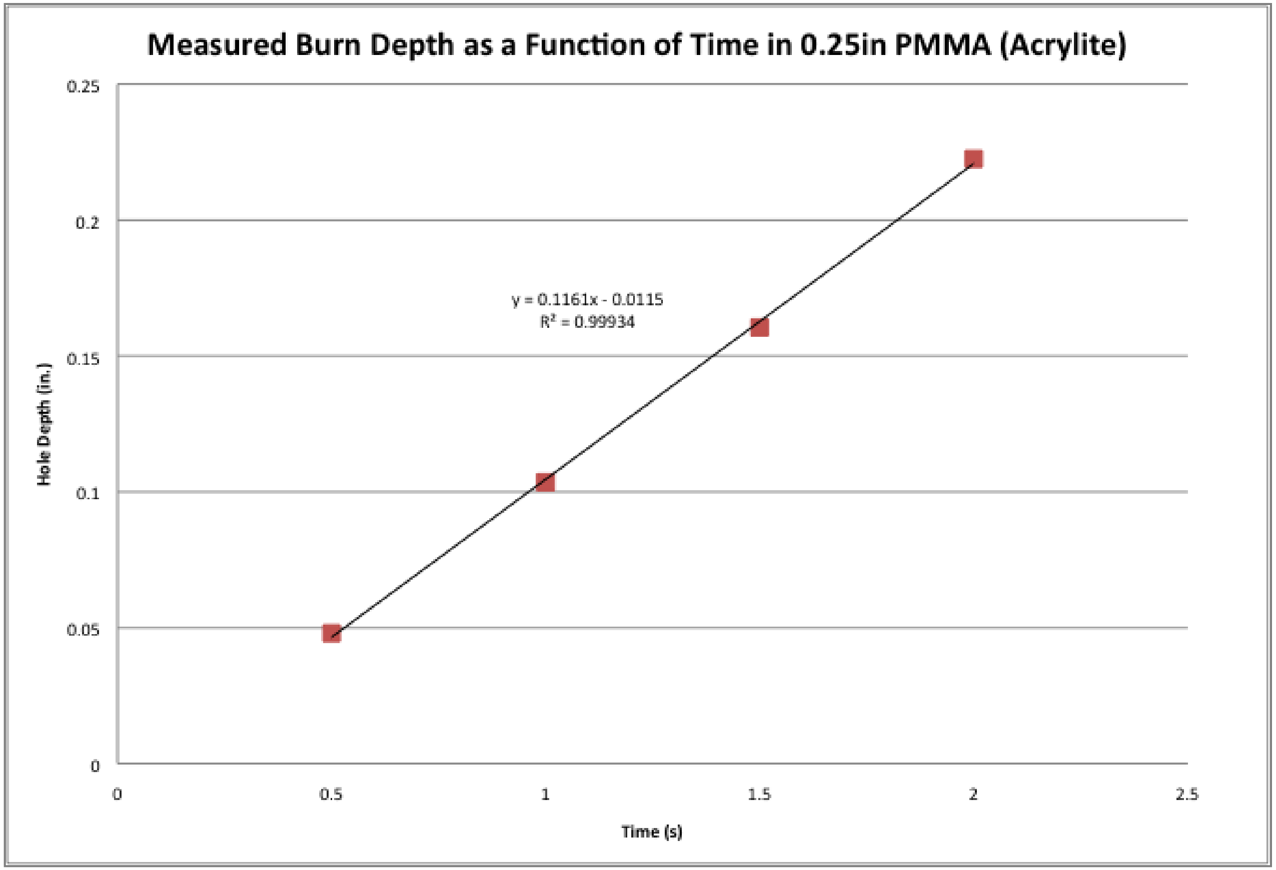


Experimental Results (Part 1): Laboratory Setup and Test Plan

- Laser Power: 110W
- Specimen Thicknesses:
  - 0.25 in.
  - 0.5 in.
- Experimental Procedure:
  - Laser Drill Specimens for Specified Times.
  - Measure Local Sample Thickness Away From Hole.
  - Measure Hole Depth.

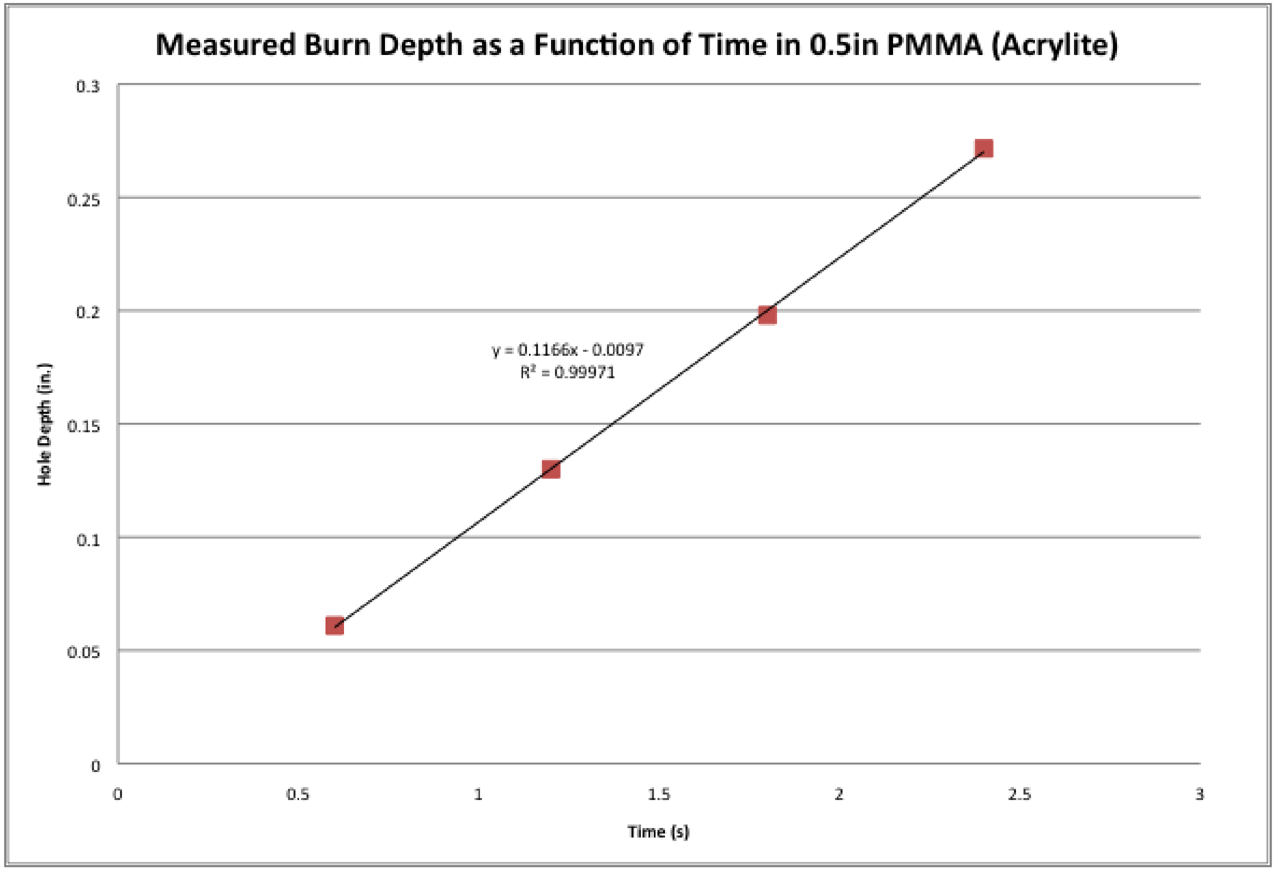
Experimental Results (Part 2): Depth vs. Irradiance Time for 0.25in PMMA

- Largest Predicted Hole Diameter (Front Surface): 0.298 in.
- Hole Evolution Rate: 0.116 in/s.



Experimental Results (Part 3): Depth vs. Irradiance Time for 0.50in PMMA

- Largest Predicted Hole Diameter (Front Surface): 0.298 in.
- Hole Evolution Rate: 0.117 in/s.



Comparisons and Conclusions

- COMSOL Multiphysics Model:
  - Burn-through Rate: 0.136 in/s
  - Largest Hole Diameter: 0.291 in.
- Experimental Results:
  - Burn-through Rate: 0.117 in/s
  - Largest Hole Diameter: 0.298 in.
- Model Deviation from Experiment:
  - 20% Overprediction of Burn Rate
  - 2% Underprediction of Hole Diameter

Acknowledgements

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Thank you for your attention!

Any Questions?