SAND2016-5162C

Composite Propellant Characterization and Combustion Modeling

Graham Kosiba[a], Ryan Wixom[b], Matthew Oehlschlaeger[a]

[a]Rensselaer Polytechnic Institute
[b]Sandia National Laboratories

Objectives

The current project uses image processing and stereological techniques to capture the heterogeneity of composite propellant in a predictive burn rate model.

- Composite propellant samples made up of ammonium perchlorate(AP), Hydroxyl-terminated polybutadiene(HTPB), and aluminum(Al) are faced with an ion mill and imaged with a scanning electron microscope(SEM).
- Properties of both the bulk and individual components of the composite propellant are determined from a variety of image processing tools.
- An algebraic model predicts the steady-state burning of the aluminized composite propellant.

Introduction

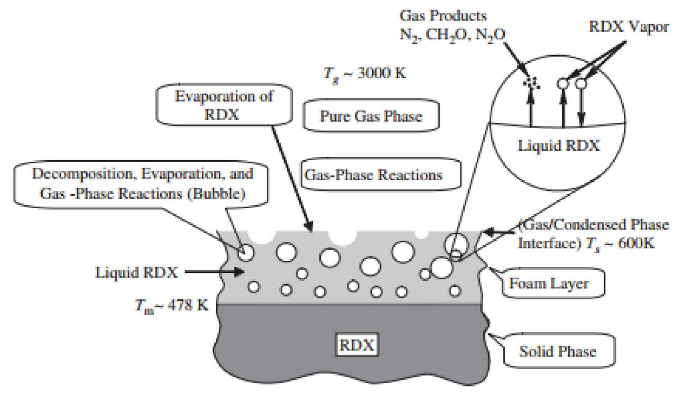

Figure: Solid Propellant Combustion Schematic[1]

Combustion of solid propellant involves a coupling of the three regions: solid phase, subsurface two-phase, and a gas phase.

- The solid itself may be undergoing a number of physical processes: temperature change, chemical reaction, and phase change as decomposition.
- Heterogeneity in the solid introduces 'grain' scale microstructure effects such as temperature gradients, non-planar surface decomposition, and thus further kinetics coupling between the solid and gas.
- Generated gaseous products disperse from the surface and react in a reacting flow region forming a flame field above the solid.

Image Processing

Image processing of high fidelity 2D propellant cross-sections provides sample specific and general input parameters for modeling.

- Mean particle sizes
- Surface areas
- Bulk propellant mixture values

The starting image file is imported and is grayscale. There are three material phases in the image of interest, ammonium perchlorate(AP), binder(HTPB), and aluminum(Al).

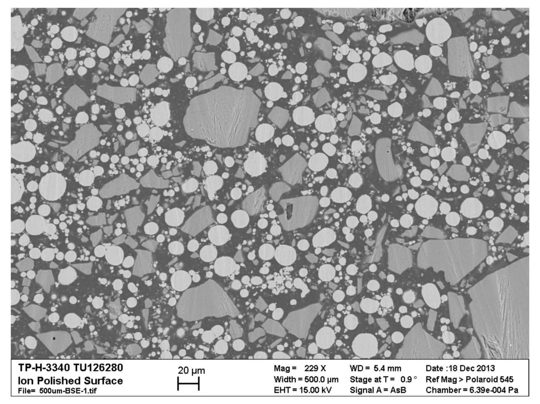

Figure: Grayscale Propellant SEM Image: Sample A

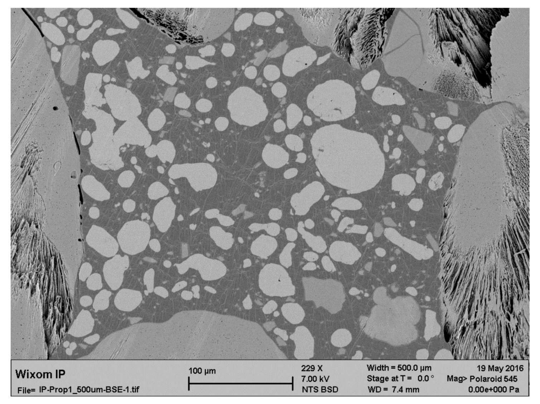

Figure: Grayscale Propellant SEM Image: Sample B

Thresholding the grayscale image separates the three phases into binary mappings.

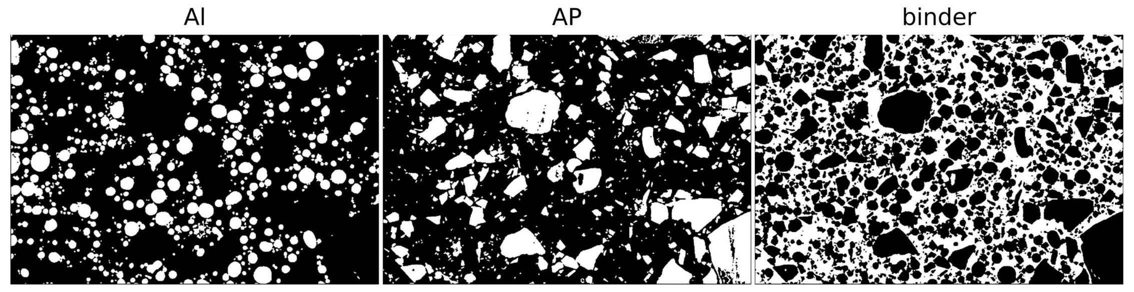

Figure: Binary Images of the Three Thresholded Phases: Sample A

Watershed segmentation separates individual AP and Al particles allowing individual measurements.

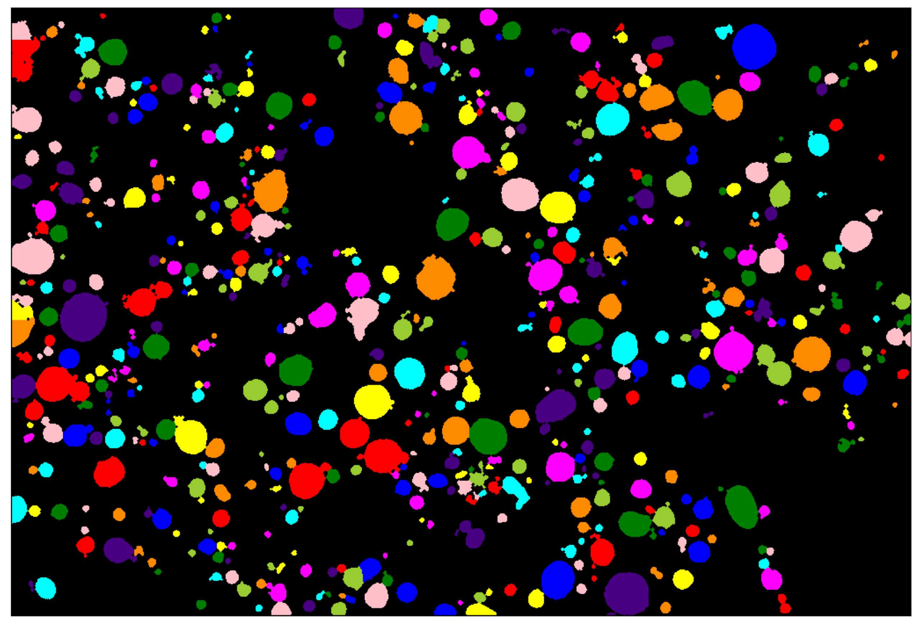

Figure: Segmented Al Particles: Sample A

Stereology

The point-sampled intercept method estimates volume-weighted mean particle volume from two independent measurements, eliminating sampling bias[2].

- The first measurement in this technique is to select features for measurement from an overlaid point grid
- From points that lie within a particle, a line is drawn and measured in a random direction to the particle boundary
- This process is repeated; the average line length is the volume-weighted mean particle diameter

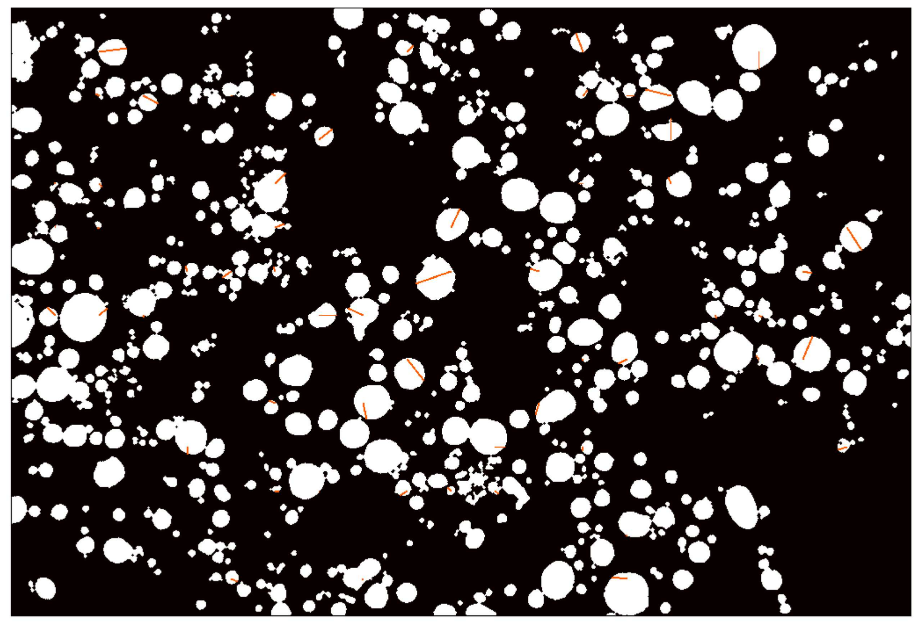

Figure: Point-Sampled Intercept Lines: Sample A

Image Processing Results

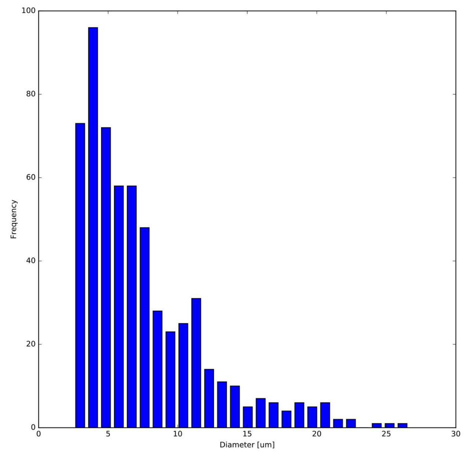

Figure: Histogram of intersected Al particle diameters: Sample A

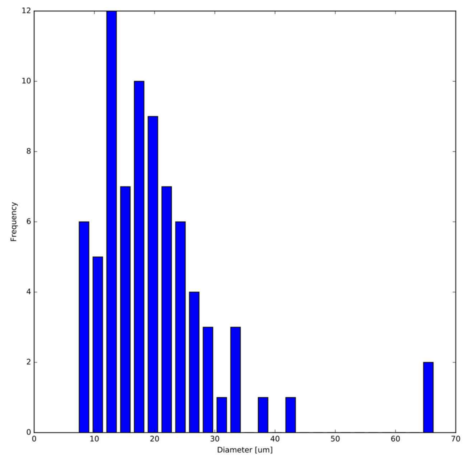

Figure: Histogram of intersected Al particle diameters: Sample B

Table: Solid Propellant Characterization Measurements: Sample A

$SA_{Al} = 2154.69\,[\mu m^2]$	$SA_{AP} = 43446.77\,[\mu m^2]$	$SA_{binder} = 123421.52\,[\mu m^2]$
$\bar{d}_{Al} = 1.607\,[\mu m]$	$\bar{V}_{p,Al} = 17.405\,[\mu m^3]$	$V_{V,Al} = 1.27\%$
$V_{V,AP} = 25.70\%$	$V_{V,binder} = 73.02\%$	

Table: Solid Propellant Characterization Measurements: Sample B

$SA_{Al} = 755.31\,[\mu m^2]$	$SA_{AP} = 107665.25\,[\mu m^2]$	$SA_{binder} = 60602.42\,[\mu m^2]$
$\bar{d}_{Al} = 2.17\,[\mu m]$	$\bar{V}_{p,Al} = 42.94\,[\mu m^3]$	$V_{V,Al} = .446\%$
$V_{V,AP} = 63.6\%$	$V_{V,binder} = 35.8\%$	

Combustion Model

The model consists of the improved Beckstead-Derr-Price model developed by Cohen and Strand[3] as well as an introduction of aluminum particles.

- Surface regression is tied to an assumed gas phase flame region: 1) a primary diffusion flame between the decomposition products of the binder and oxidizer and 2) a premixed oxidizer flame.
- Aluminum within the solid acts as a heat sink and does not react until gas phase, increasing propellant adiabatic flame temperature
- Properties derived from the image processing are used as model inputs directly, leading to a sample specific predictive combustion model

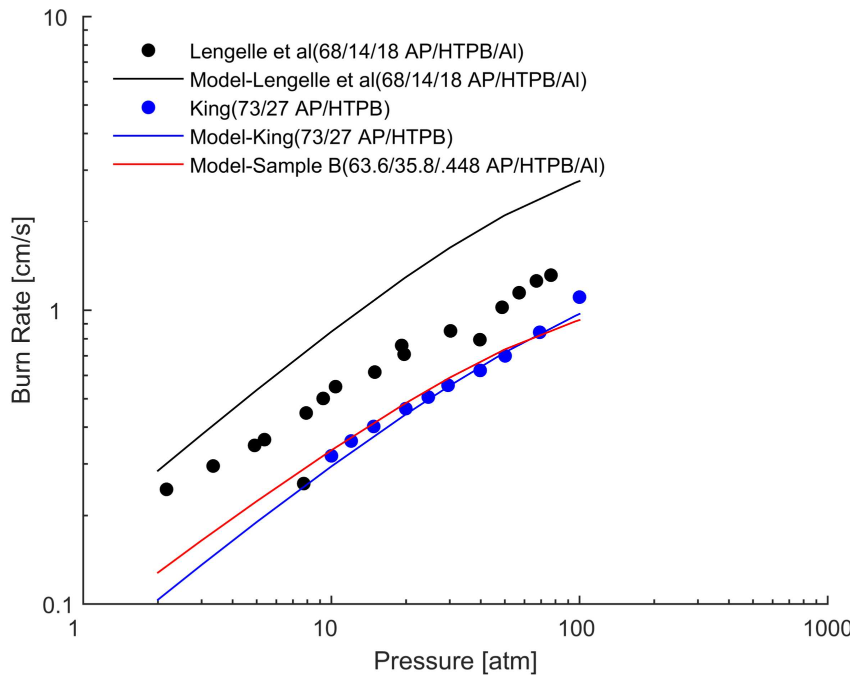

Figure: Composite Propellant Predicted Burn Rate and Experimental Values[4, 5]

References

[1] M. W. Beckstead, K. Puduppakkam, P. Thakre, V. Yang. "Modeling of Combustion and Ignition of solid-propellant ingredients". In: *Progress in Energy and Combustion Science* 33 (2007), pp. 497–551.

[2] Russ, John C & Neal, Brent F. *The Image Processing Handbook*. CRC press, 2015.

[3] N. S. Cohen and L. D. Strand. "An Improved Model for the Combustion of AP Composite Propellants". In: *AIAA Journal* 20.12 (1982), pp. 1739–1746.

[4] G. Lengelle, J. Duterque, J.F. Trubert. "Combustion of Solid Propellants". In: *RTO-EN-023. Presented at RTO/VKI Special Course on 'Internal Aerodynamics in Solid Rocket Porpulsion'* (2002).

[5] M. K. King. "Erosive Burning of Composite Solid Propellants: Experimental and Modeling Studies". In: *Journal of Spacecraft and Rockets* 16.3 (1979), pp. 154–162.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.