Thermo-poro-mechanical modeling of RTV intumescence

Sreevishnu Oruganti[a,b,*], Sergio Fraile Izquierdo[C], Nagi N. Mansour[a,b] and Francesco Panerai[a,b]

[a]*Center for Hypersonics and Entry Systems Studies, University of Illinois-Urbana Champaign, IL-61801, USA*
[b]*Department of Aerospace Engineering, University of Illinois-Urbana Champaign, IL-61801, USA*
[c]*Analytical Mechanical Associates Inc. Moffett Field, CA-94035, USA*

Abstract

Room temperature vulcanizing (RTV) silicone is a high-temperature adhesive used as a gap-filler between heatshield tiles in numerous entry missions. Its propensity to intumesce, or swell upon exposure to heat, is a well-known effect that needs to be carefully quantified during design. At tile interfaces of charring ablators, intumescence, combined with differential recession, could cause the gap filler to protrude past the ablator outer mold line, forming a "fence". Fencing can in turn cause transition to turbulence of the flow wetting the heat shield, leading to augmented surface heating. Recent experiments conducted at the Plasmatron X facility, the high enthalpy wind tunnel of the Center for Hypersonics and Entry Systems Studies, have shown prominent fencing of RTV gap fillers in PICA, under both nitrogen and air plasmas [1,2]. Similar observations are well known in the arcjet literature. Further experiments under controlled environment, performed using *in situ* X-ray micro-computed tomography (micro-CT) at the Advanced Light Source (ALS), have shown heating rate-dependent swelling and shrinkage of RTV during pyrolysis [3–5].

To simulate RTV intumescence, a novel model was introduced in the Porous Materials Analysis Toolbox based on OpenFOAM, PATO [6], to account for pore-pressure buildup within both closed- and open-pores [7]. The governing equation for the thermo-poro-mechanical response were developed, assuming linear elasticity for the charring silicone. A new *multi-pyrolysis* model that tracks non-monotonic advancement of material properties with pyrolysis was proposed. This model addresses the limitations of state-of-the-art ablator models to capture the different stages of thermal degradation and coupled thermomechanics.

Swelling of RTV was simulated using the new thermo-poro-mechanical model and compared against *in situ* micro-CT data. Results showed good agreement in intumescence height and temperature profiles at all heating rates, indicating that the key factor contributing to RTV swelling is the internal pressure build-up within closed- and open-pores. As RTV is cured into a soft (rubbery) compound with low-porosity and permeability, initial temperature increase and pyrolysis gas production cause a significant increase of internal pressure, causing a pronounced volume growth. As thermal degradation progresses, rigidization of the silicone occurs due to char hardening which counteract volume shrinkage after gas pressure relief. Overall, our model shows that accounting for changes in properties such porosity, permeability and key thermomechanical coefficients is crucial for capturing the RTV volume change during ablation and enable a predictive capability for heatshield tile interface response. A plan for future calibration of thermomechanical properties evolution during degradation is discussed, as a key next step to close the new model.

Keywords: *silicone intumescence, thermo-poro-mechanical material modeling, micro-tomography, thermal protection system*

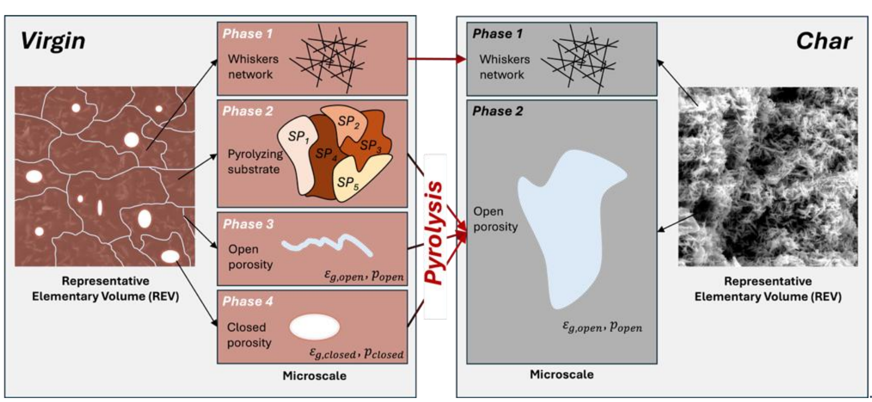

Figure 1: Representative elementary volume (REV) of virgin and charred RTV.

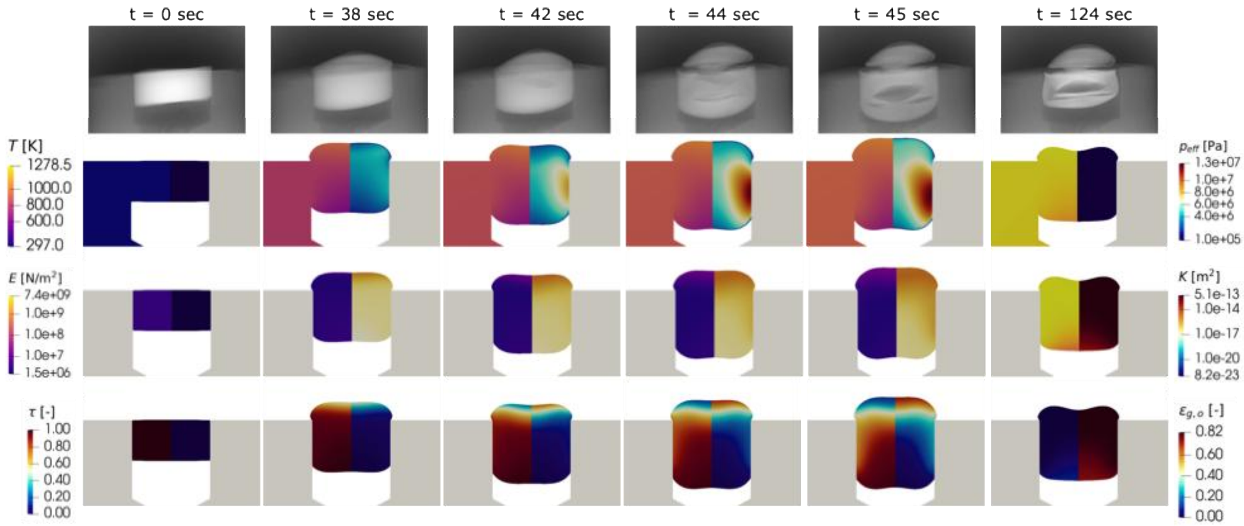

Figure 2: Thermo-poro-mechanical simulations at 1946 °C/min compared with radiographs at selected time points. Contours show temperature and effective pressure, Young's modulus and permeability, advancement of pyrolysis and volume fraction of open porosity, respectively.

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