TFAWS Aerothermal Paper Session

Assessing the Effects of Various Surface Textures and Features on Turbulent Heat Transfer in Hypersonic Flight

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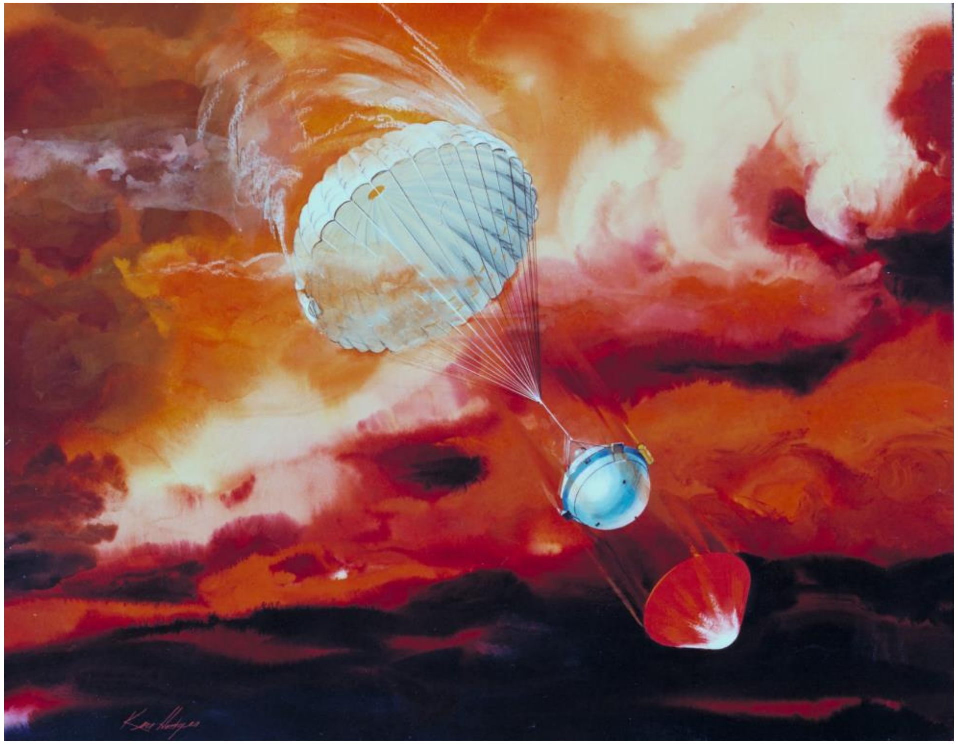
Outline

- Introduction
- Approach
- Description of the Experiments
- Results
- Summary

Artist's Rendering of Galileo Probe at Jupiter

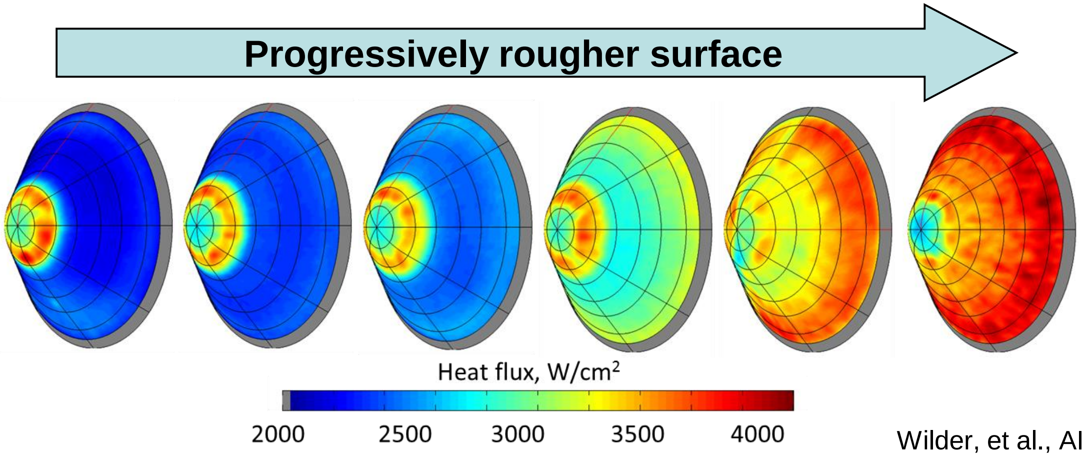


NASA Artwork by Ken Hodges

Introduction

- Thermal Protection System (TPS) materials used on atmospheric entry vehicles have surface roughness characteristic of the material and fabrication methods
- Surface roughness can evolve in response to ablation and other mechanisms that occur during exposure to the flight environment
- The roughness can affect the boundary layer state, and can lead to significant increases in heating rates

Example: Heat flux on 45° sphere-cone models in flight at Mach 10



Wilder, et al., AIAA-2014-0512

Introduction

- This research focuses on the effects on turbulent heat transfer due to surface roughness of types relevant to NASA entry missions, and was supported by NASA's Entry Systems Modeling (ESM) Project
- The emphasis was on new classes of woven materials, which are enabling for many missions
  - Heatshield for Extreme Entry Environment Technology (HEEET)
  - 3-D Medium Density Carbon Phenolic (3MDCP)*

Texture of the woven surface

Steps at seams for tiled configurations

Cavities due to impact damage (not shown)

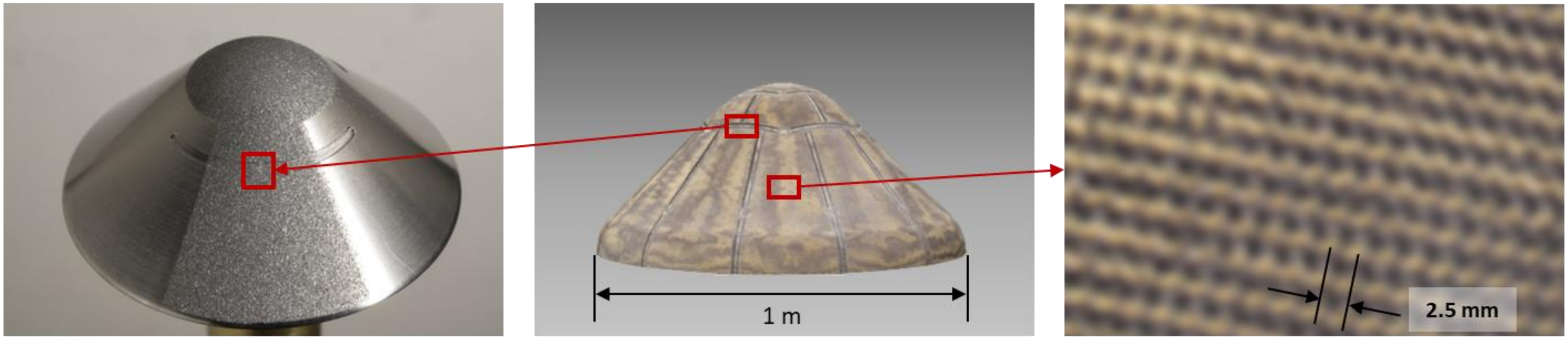
HEEET Engineering Test Unit
https://www.nasa.gov/centers/ames/thermal-protection-materials/tps-materials-development/woven.html

*Ellerby, D., et al. (2021). TPS and Entry Technologies for Future Outer Planet Exploration. Bulletin of the AAS, 53(4). https://doi.org/10.3847/25c2cfeb.9453cc81

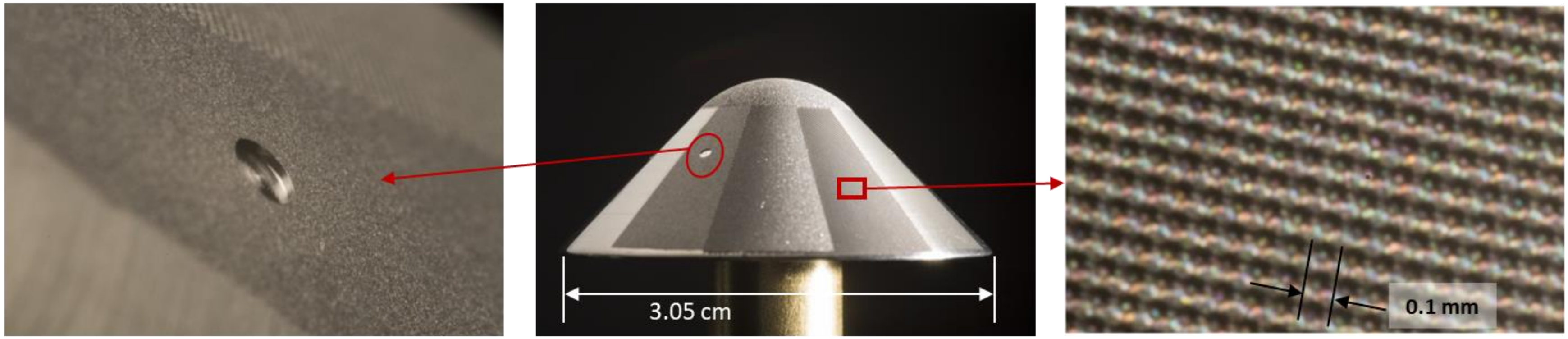
Approach

- Ballistic range models were fabricated to provide several regions of surface texture, and/or roughness features, including
  - Scaled patterns representative of woven TPS
  - Sand-grain roughness, as a reference texture
  - Grooves representative of tiled-HEEET seams at various locations, length/depth, surrounding roughness
  - Isolated cavities at several locations, length/depth ratios, surrounding roughness
  - Smooth-wall sections to provide a reference heat-flux measurement on each test

Seam Representation on Ballistic-Range Model | **Dual-Layer HEEET Engineering Test Unit** | **Detail of HEEET Recession Layer**



Cavity Representation on Ballistic-Range Model | **Ballistic-Range Model with Several Textures** | **Detail of Ballistic-Range Model "Woven" Surface**

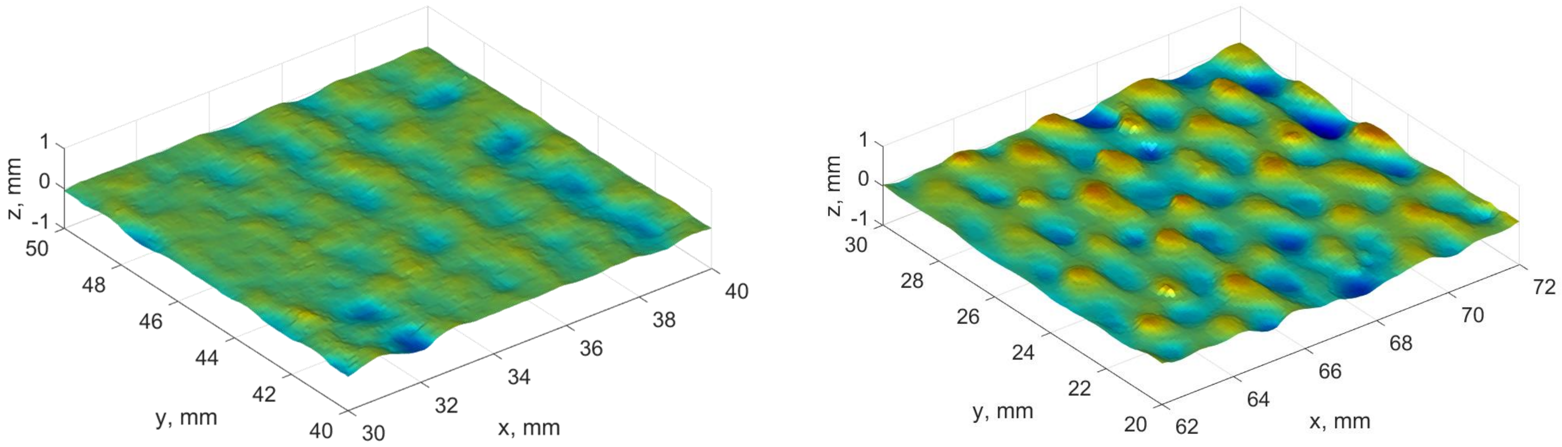


Approach

- Woven TPS surface textures were based on measurements of the HEEET material made before, and after exposure to high-heating arc jet environments*

Surface Scan of Pre-Test Material

Surface Scan of Post-Test Material

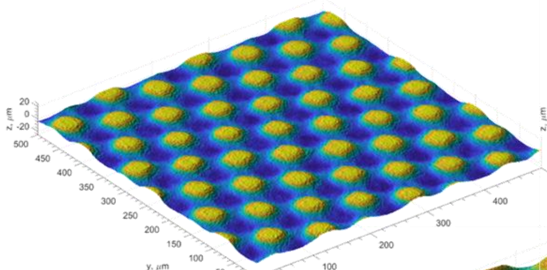


*Venkatapathy, E., *et al.*, "TPS for Outer Planets," Outer Planets Assessment Group (OPAG) Technology Forum; 21-22 Feb. 2018

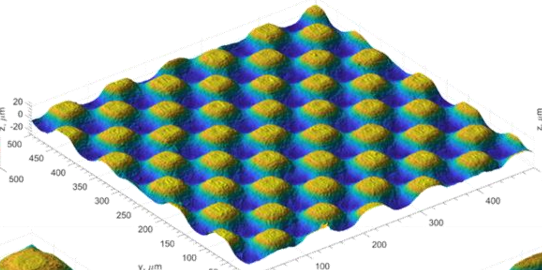
Approach

- Results for five patterns were previously reported
  - Three representing the Recession Layer (RL) of dual-layer HEEET at various levels of ablation
  - One representing the HEEET Insulation Layer (IL), or the 3MDCP derivative
  - One, a control variation on IL, in which the valleys in the wavy pattern are filled

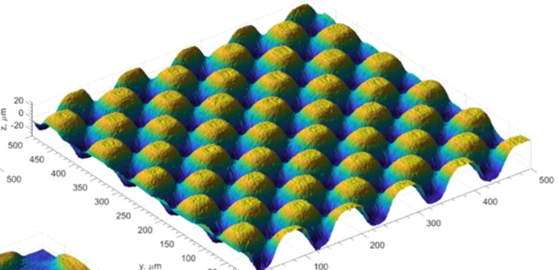
“Virgin” RL Pattern
Nominal element height = 10 μm

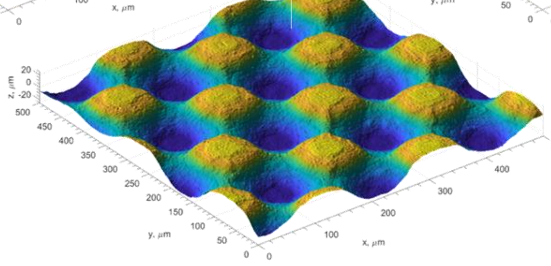


“Ablated” RL Pattern
Nominal element height = 20 μm

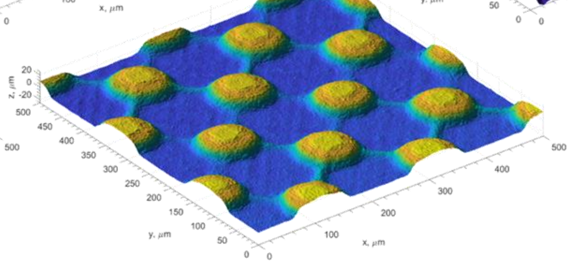


2x “Ablated” RL Pattern
Nominal element height = 40 μm





“Ablated” IL Pattern
Nominal element height = 40 μm
Nominal element spacing = 2x RL spacing



“Ablated” IL Pattern with only the peaks (PO)
Nominal element height = 20 μm

Approach

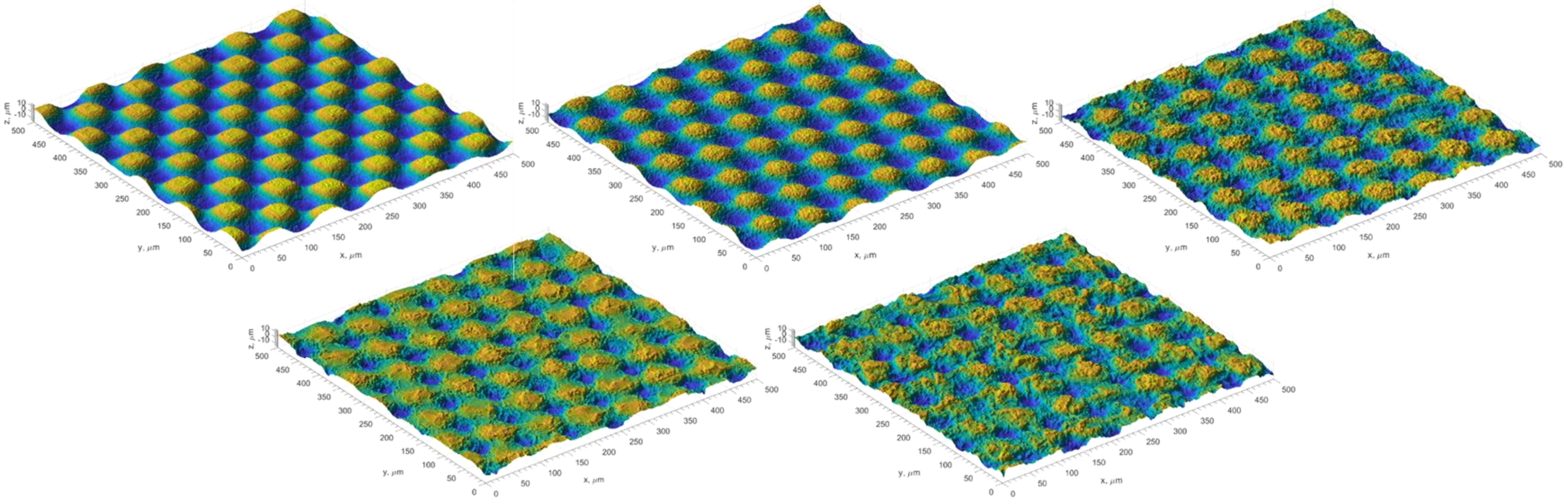
- New results reported here were obtained on the patterns representing ablated Recession Layer (RL) and ablated Insulation Layer (IL), shown on the previous slide, with each eroded by sand-blasting with various micro-abrasives to more closely represent flight-like surfaces

Roughened RL Patterns

“Ablated” RL Pattern, as Fabricated
Nominal element height = 20 µm
Nominal element spacing = 100 µm

Roughened with 400-grit AlOx
Average particle size = 22 µm

Roughened with 220-grit AlOx
Average particle size = 63 µm



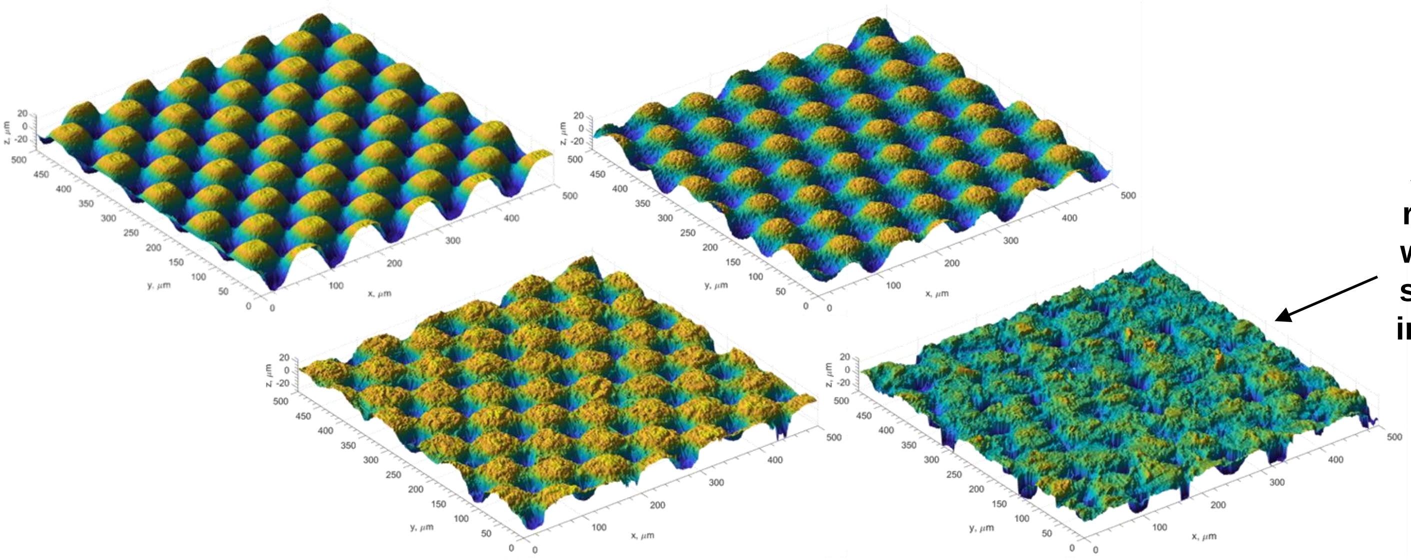
Roughened with B120 microspheres
Average particle size = 102 µm

Roughened with 120-grit AlOx
Average particle size = 102 µm

Approach

- RL patterns having 40 μm initial element height were more severely eroded for the larger the larger abrasives
- The original wavy pattern is still identifiable, and individual roughness elements could be found by the roughness analysis approach

Roughened 40 μm RL Patterns



2x "Ablated" RL Pattern
Nominal element height = 40 μm

Roughened with 400-grit AlOx
Average particle size = 22 μm

Roughened with 220-grit AlOx
Average particle size = 63 μm

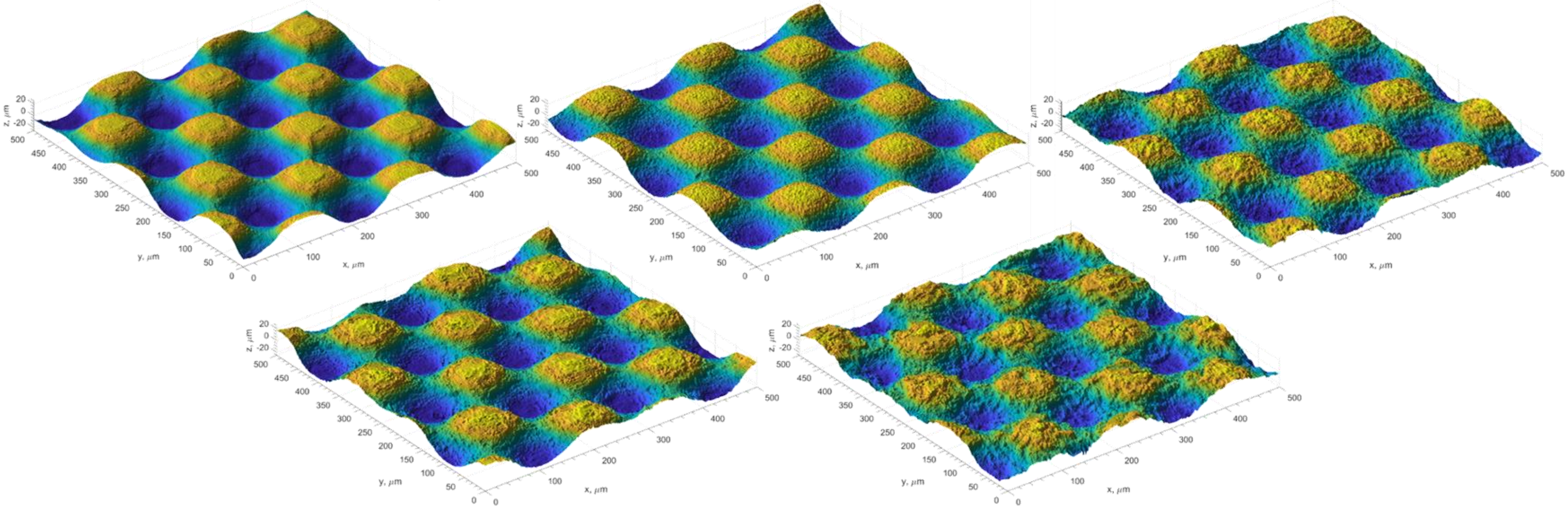
Roughened with 120-grit SiC
Average particle size = 102 μm

Silicon Carbide, rather than AlOx, was used for this sample, resulting in greater erosion

Approach

- For the IL patterns the micro-abrasive particle mean size was less than the wavelength of the roughness pattern
- As a result the surface was roughened, but the wavy pattern was not significantly degraded, in contrast to the RL patterns

Roughened IL Patterns



"Ablated" IL Pattern, as Fabricated
Nominal element height = 40 μm
Nominal element spacing = 200 μm

Roughened with 400-grit AlOx
Average particle size = 22 μm

Roughened with 220-grit AlOx
Average particle size = 63 μm

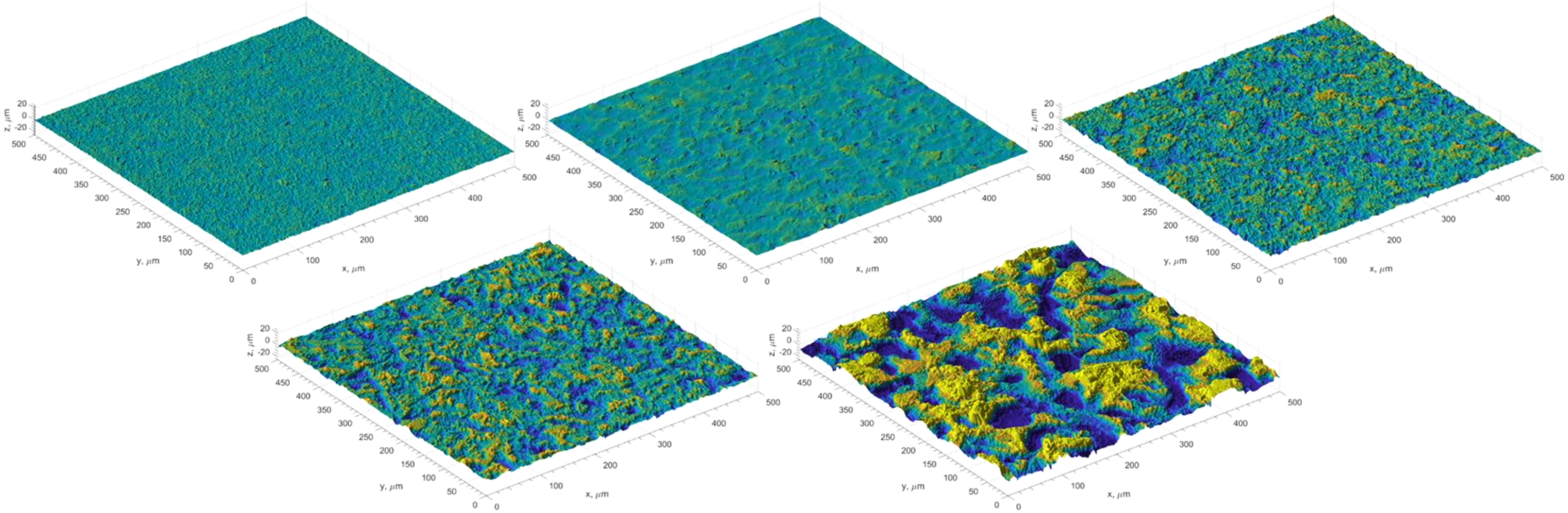
Roughened with B120 microspheres
Average particle size = 102 μm

Roughened with 120-grit AlOx
Average particle size = 102 μm

Approach

- Results were also obtained on sand-blasted surfaces, giving a close analog of sand-grain roughness
  - A similar processed was use by the Passive Nosetip Technology (PANT) Program
    - Wool, M. R., Aerotherm Report 75-159, June 1975

Sand-Blasted Surfaces



Roughened with 400-grit AlOx
Average element height = 2.4 µm

Roughened with B120 microspheres
Average element height = 2.5 µm

Roughened with 220-grit AlOx
Average element height = 5.7 µm

Roughened with 120-grit AlOx
Average element height = 6.6 µm

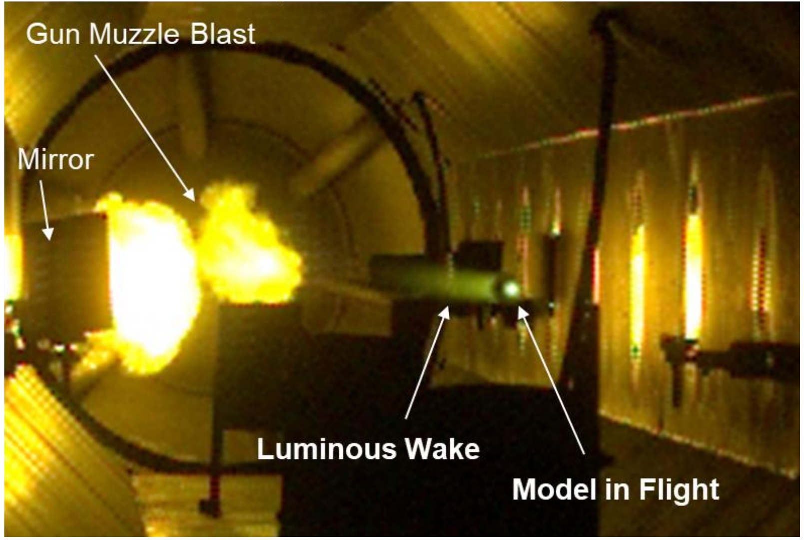
Roughened with 60-grit SiC
Average element height = 19.4 µm

Test Facility

- The models were flown in the Ballistic Range Complex at NASA Ames
  - Tests were done at Mach 9 to 10 in air
  - Roughness Reynolds numbers, k^+ (based on roughness height) were between 10 and 200
- Hypervelocity Free Flight Aerodynamic Facility (HFFAF)
  - NASA's only controlled-atmosphere free-flight aeroballistic range
  - Launch speeds up to ~8 km/s
  - Test section pressure from 1 atm to vacuum
  - Test in various gases (Air, N_2, CO_2, Ar, H_2/He, etc.)
  - For additional details, see Wilder, *et al*., AIAA-2015-1339, or visit https://www.nasa.gov/centers/ames/thermophysics-facilities/ballistic-ranges

Exterior of the Test Section

Interior View with Model in Flight



Test Conditions

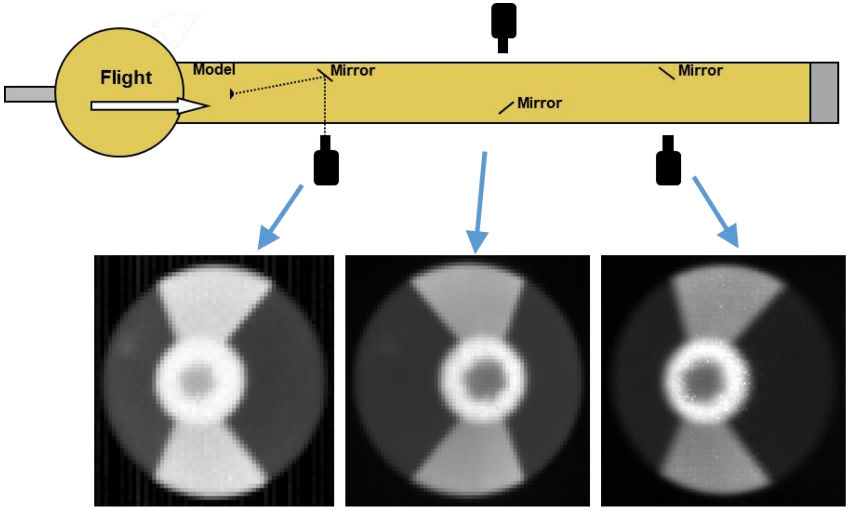
- All tests were conducted in room temperature air
- Two nominal test conditions, and one shot off-nominal due to a launch issue
  - (4 shots) Average V = 3 km/s, P_∞ = 114 Torr, $Re_D = 0.9 \times 10^6$, $0.01 < k/\delta < 0.2$
  - (4 shots) Average V = 3.2 km/s, P_∞ = 152 Torr, $Re_D = 1.2 \times 10^6$, $0.01 < k/\delta < 0.2$
  - (1 shot) Average V = 3.8 km/s, P_∞ = 152 Torr, $Re_D = 1.5 \times 10^6$, $0.03 < k/\delta < 0.23$
- Models were free to pitch, and executed 3-4 cycles of oscillation
  - α_{RMS} < 2 deg for all shots
- Wall temperature and heat flux given below were on the smooth-wall sections of each model, averaged between $1.55 < s/R_n < 1.85$
  - Smooth-wall T_w used to evaluate boundary-layer parameter from CFD solutions
  - Smooth-wall q_w provides the baseline heat flux when evaluating heat-flux augmentation

shot	**model**	**material**	**V_0, m/s**	**mid-range V, m/s**	**Re_D (mid range)**	**α_{RMS}, deg**	**T_w, K**	**q_w, W/cm^2**	**Features**
2846	MRR 22	Titanium	3286	3048	9.18E+05	1.8	683	2250	6 roughness types
2847	MRR 24	Titanium	3216	2974	8.88E+05	1.9	665	2108	6 roughness types
2848	MRR 21	Titanium	3249	3024	9.13E+05	1.7	668	2143	6 roughness types
2849	MRR 28	Titanium	3232	2997	8.87E+05	1.7	665	2031	4 grooves, sand roughness
2850	MRR 26	Titanium	3542	3209	1.27E+06	1.4	785	3331	6 roughness types
2851	MRR 25	Titanium	3547	3211	1.27E+06	1.1	783	3309	6 roughness types, 4 cavities
2852	MRR 27	Titanium	3546	3211	1.26E+06	1.3	782	3321	6 roughness types, 3 cavities
2853	MRR 23	Titanium	4168	3774	1.47E+06	1.4	1044	6285	6 roughness types, 4 cavities
2854	MRR 29	Titanium	3537	3202	1.25E+06	1.9	771	3266	3 grooves, sand roughness

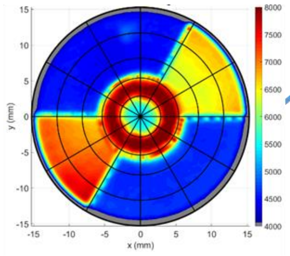
Measurement Approach

- Surface temperature of the projectile was determined from thermal images captured at several points along the flight path (as sketched below)
- Convective heat flux was inferred from the temperature images, assuming the model can be treated as a semi-infinite wall
  - Based on method of Compton and Cooper, NASA TN D-2871, June 1965.
  - Details can be found in Wilder, *et al*., AIAA-2011-3476

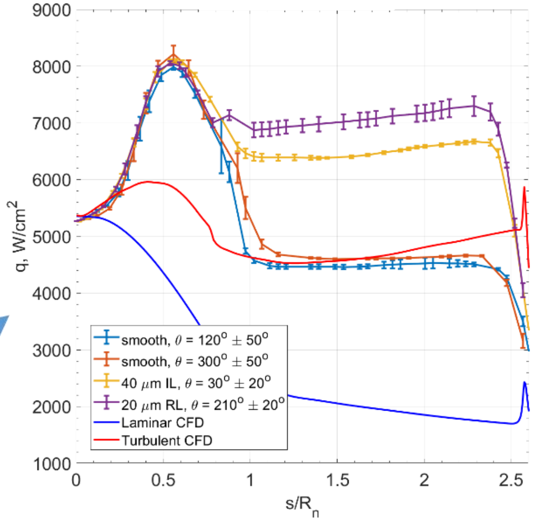
Imaging Setup along Test Section



Convective Heat Flux



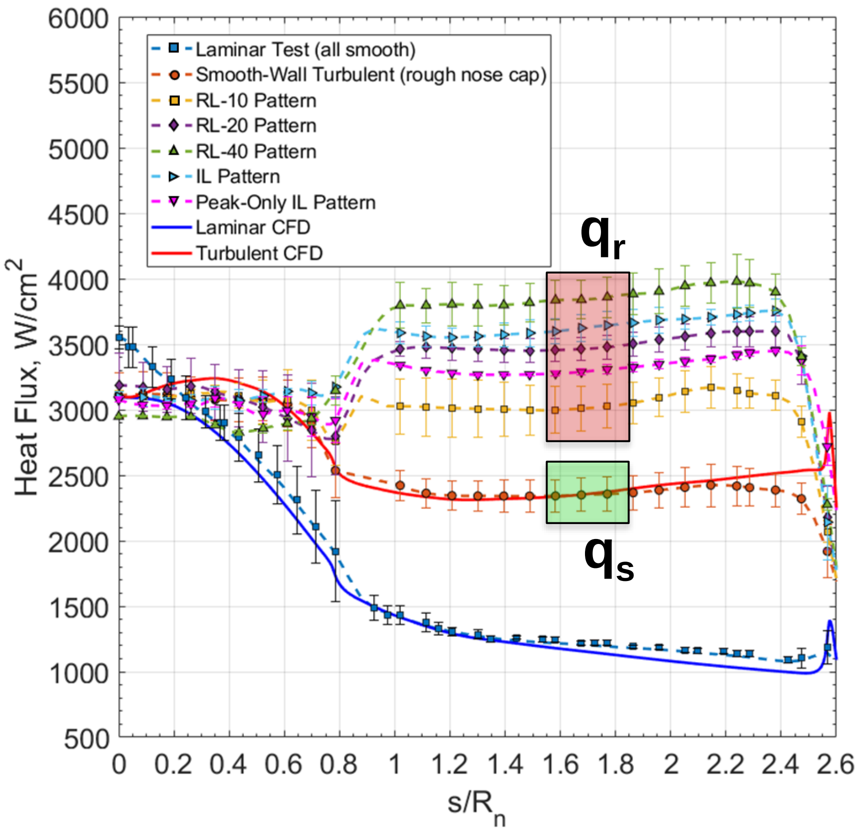
Heat Flux Profiles



Measurement Approach

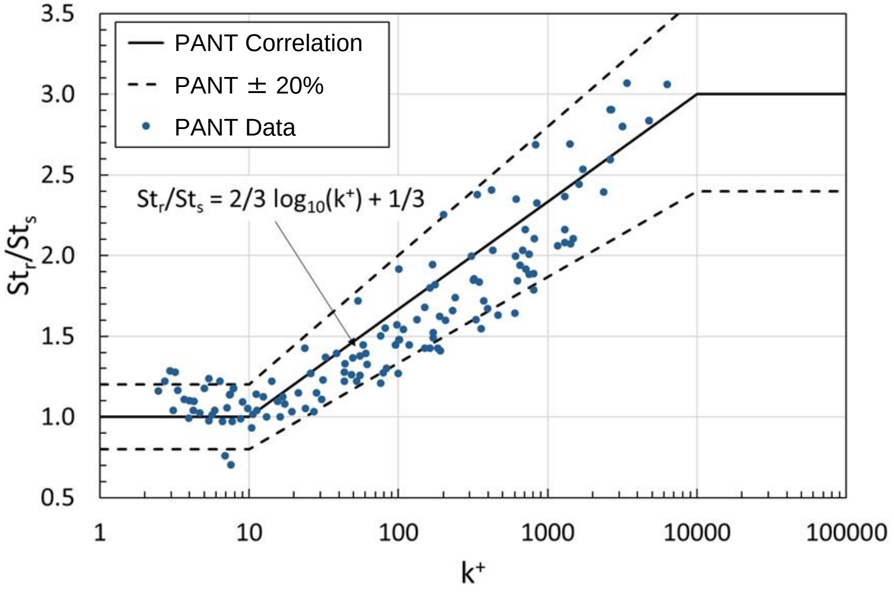
- Heat flux was averaged circumferentially through a given surface texture area, and axially on each profile for $1.55 \le s/R_n \le 1.85$
  - Computed boundary-layer properties in this region were uniform
  - $s/R_n = 1.55$ was considered sufficiently far downstream of the nose roughness (trip) for establishment of smooth-wall turbulent heat flux
  - $s/R_n = 1.85$ was considered sufficiently far upstream to avoid potential influence from the grip-line of the launch sabot

Augmentation Factor = q_r/q_s



Results

- Heat-flux augmentation for sand-grain roughness is expected to correlate with the log of the turbulent roughness Reynolds number
  - $k^+ = u_{\tau_0} k / \nu_w$, where
    - k is the average roughness element height, and
    - $u_{\tau_0} = (\tau_w / \rho_w)^{1/2}$ is the friction velocity on a smooth wall
- This correlation is illustrated by the results of the Passive Nosetip Technology (PANT) Program
  - Wool, M. R., Aerotherm Report 75-159, June 1975

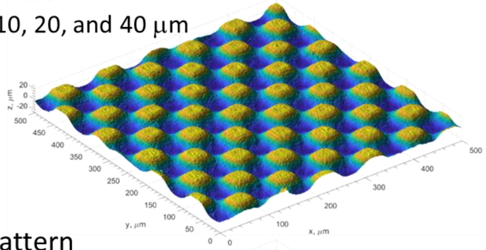


Effect of Sand Roughness on Turbulent Heat Transfer
Passive Nosetip Technology (PANT) Program

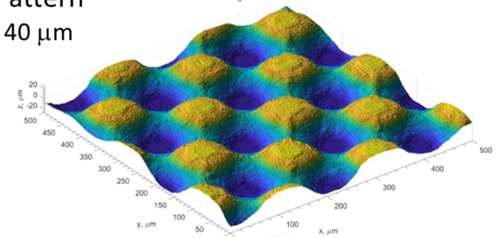
Previous Results

- Previously reported results for the un-eroded patterns
  - Generally within the bounds of the PANT data when the mean roughness element height, k, was used as the length scale in the roughness Reynolds number k^+

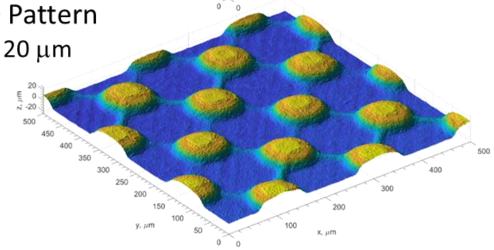
RL Patterns
k = 10, 20, and 40 μm

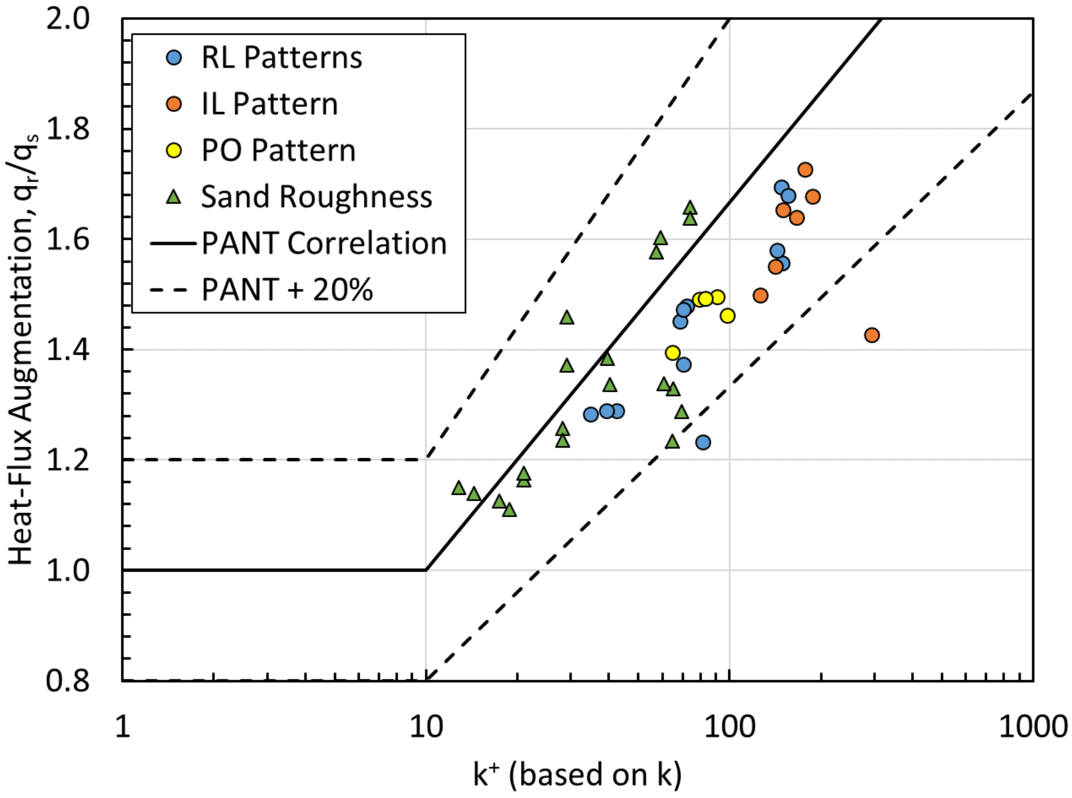


IL Pattern
k = 40 μm



PO Pattern
k = 20 μm



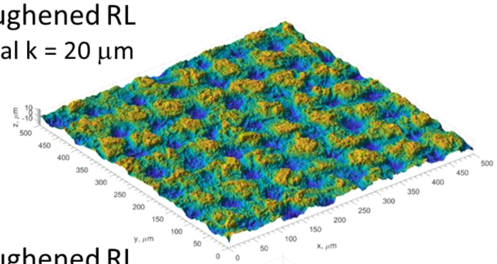


Current Results

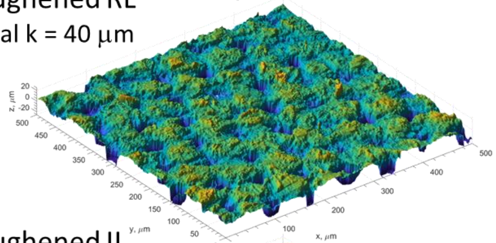
- Additional tests were performed on both the un-eroded IL and RL patterns, as well as surfaces eroded to better resemble ablated TPS surfaces
  - Also, generally within the bounds of the PANT data when the mean roughness element height, k, was used as the length scale in the roughness Reynolds number k^+

Examples of Most Eroded Surfaces

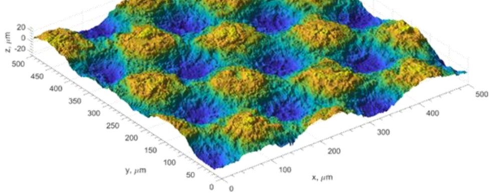
Roughened RL
Initial k = 20 µm

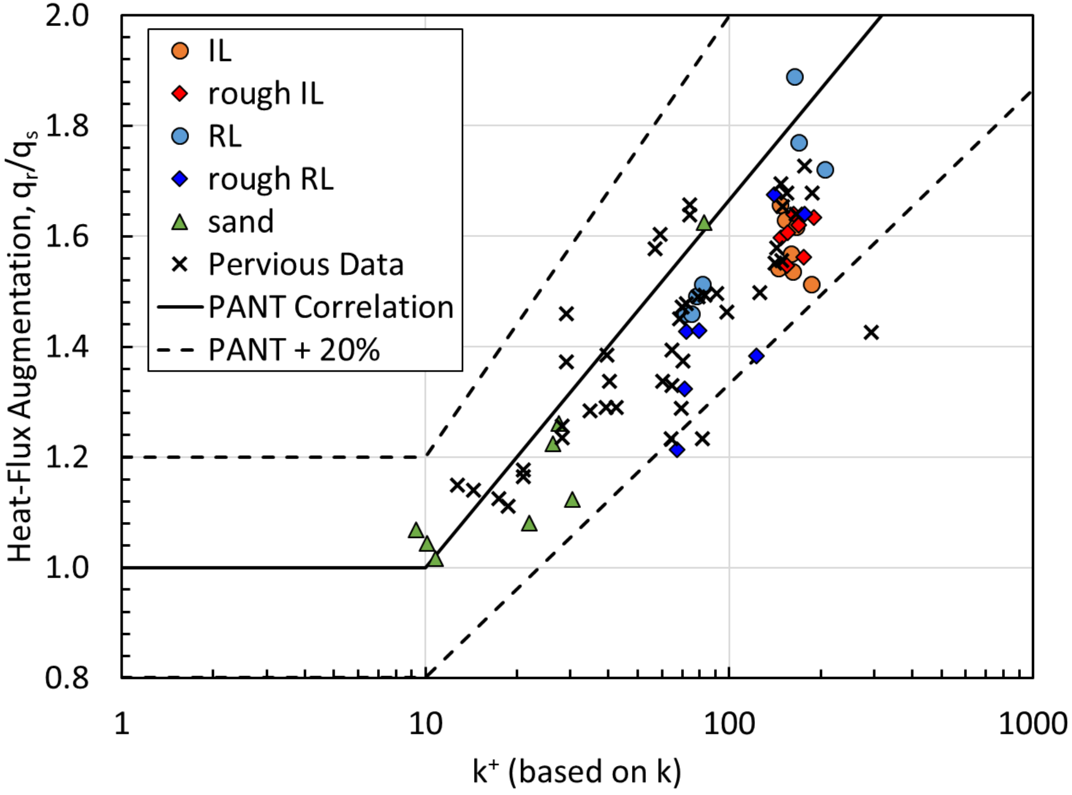


Roughened RL
Initial k = 40 µm



Roughened IL
Initial k = 40 µm

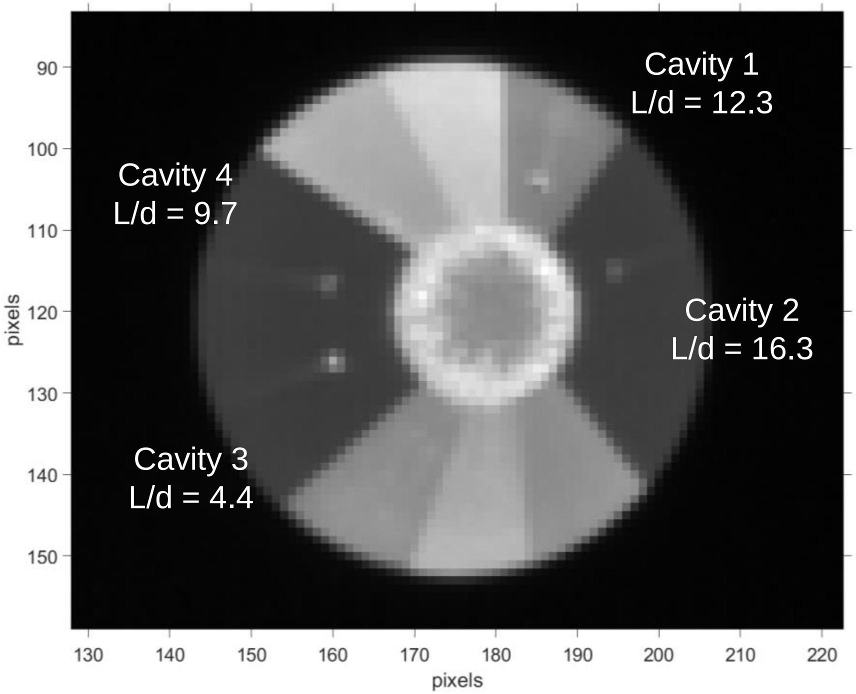


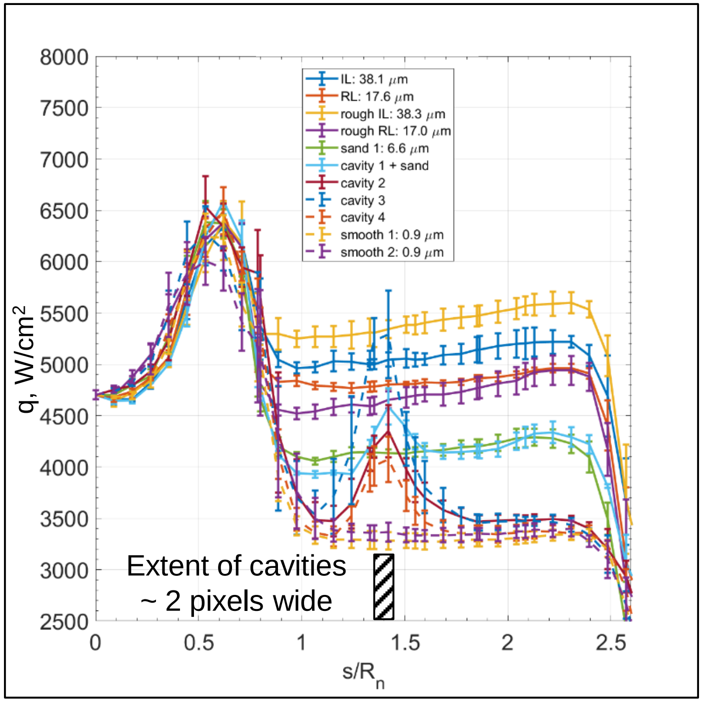


Effect of Cavities

- Several models featured isolated cylindrical cavities to represent impact damage or attachment points
  - Diameter/depth, L/d, ranged from 1.8 to 16.3
  - Depths from 0.445 mm to 0.049 mm
  - On the smooth-wall segments and the sand-blasted segments
- Configurations tested had small but measureable effect on downstream heating
- Current cameras could not resolve the heat flux internal of the cavities (only ~2 pixels across)
- Data currently being analyzed

IR Image

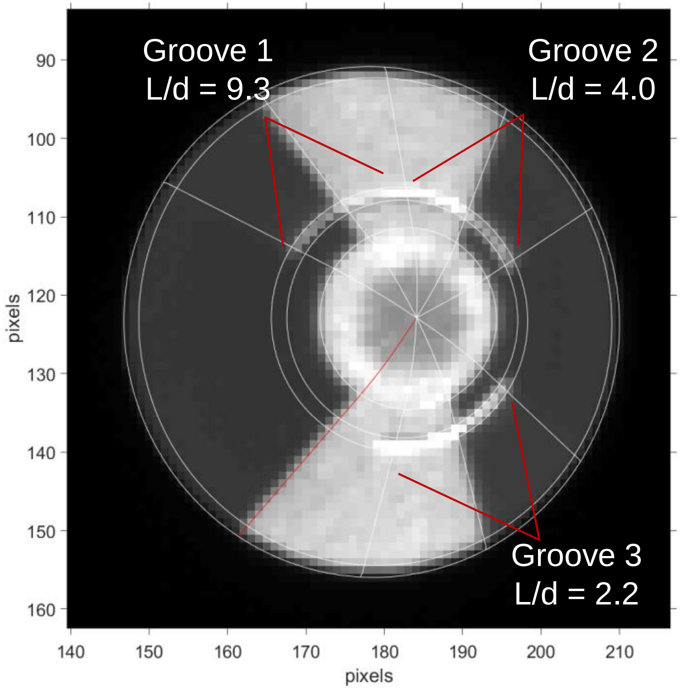


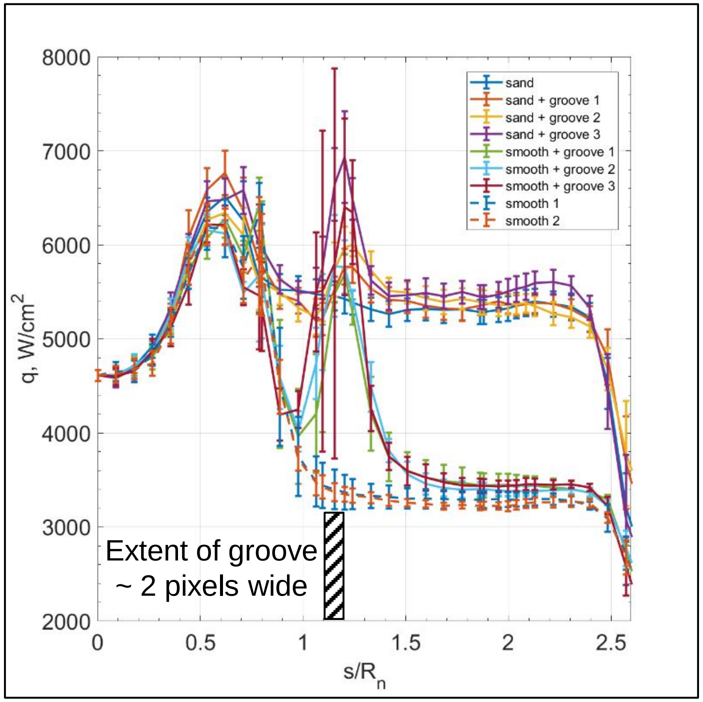


Effect of Grooves

- Grooves were machined in several models to represent steps due to differential ablation rates at seams in tiled TPS configurations
  - Length/depth, L/d, ranged from 2 to 18.2
  - Depths from 0.38 mm to 0.043 mm
  - On the smooth-wall segments and the sand-blasted segments
- Configurations tested had small but measureable effect on downstream heating
- Current cameras could not resolve the heat flux internal of the grooves (only ~2 pixels across)
- Additional tests are currently underway

IR Image





Summary

- Measurements of turbulent rough-wall heat flux have been made during hypersonic flight in a ballistic range to characterize heat-flux augmentation on roughness patterns representative of woven thermal protection system materials
- Tests were also done on eroded roughness patterns for more flight-like surface textures
- Reference measurements were made on sand grain (sand-blasted) roughness and smooth walls
- Heat-flux augmentation for the woven roughness patterns was generally less than for sand roughness of the same mean roughness element height, k, but within the measurement uncertainty
- The heat flux augmentation for both pattern and sand roughness correlated with the roughness Reynolds number, k^+, when the characteristic height was the average height of the roughness elements, k
- Tests are currently underway to characterize the effects on turbulent heat flux of isolated macroscopic features, such as cavities and seams between TPS tiles