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Investigating Surface Topography Effects on Directional Emissivity of Metallic Additively Manufactured Parts

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PhD Defense

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Agenda

- Background
- Investigating Surface Characteristics that affect Emissivity
  - Simulations
  - Experimental Measurements
- Investigating View Angle and Temperature Effects on Emissivity
- In-Situ Surface Roughness Measurement Testing
- Conclusions
- Future Work

Introduction

- Hesitancy using AM parts in safety critical applications
- Improvement of process and quality of parts achieved through in-situ monitoring
- Thermal in-situ monitoring focused on, due to relationship between thermal history and mechanical properties
- Emissivity is key factor in accuracy of thermal measurements

Background

- Metal Additive Manufacturing Processes
- Thermal Monitoring in Additive Manufacturing
- Radiation/Emissivity
- Surface Roughness Definitions
- Surface Roughness in Additive Manufacturing
- Surface Roughness and Emissivity

Direct Metal Laser Sintering (DMLS)

- Popular AM technique
- Layer-wise process
- Argon or nitrogen atmospheres
- Extreme thermal gradients resulting in residual stresses

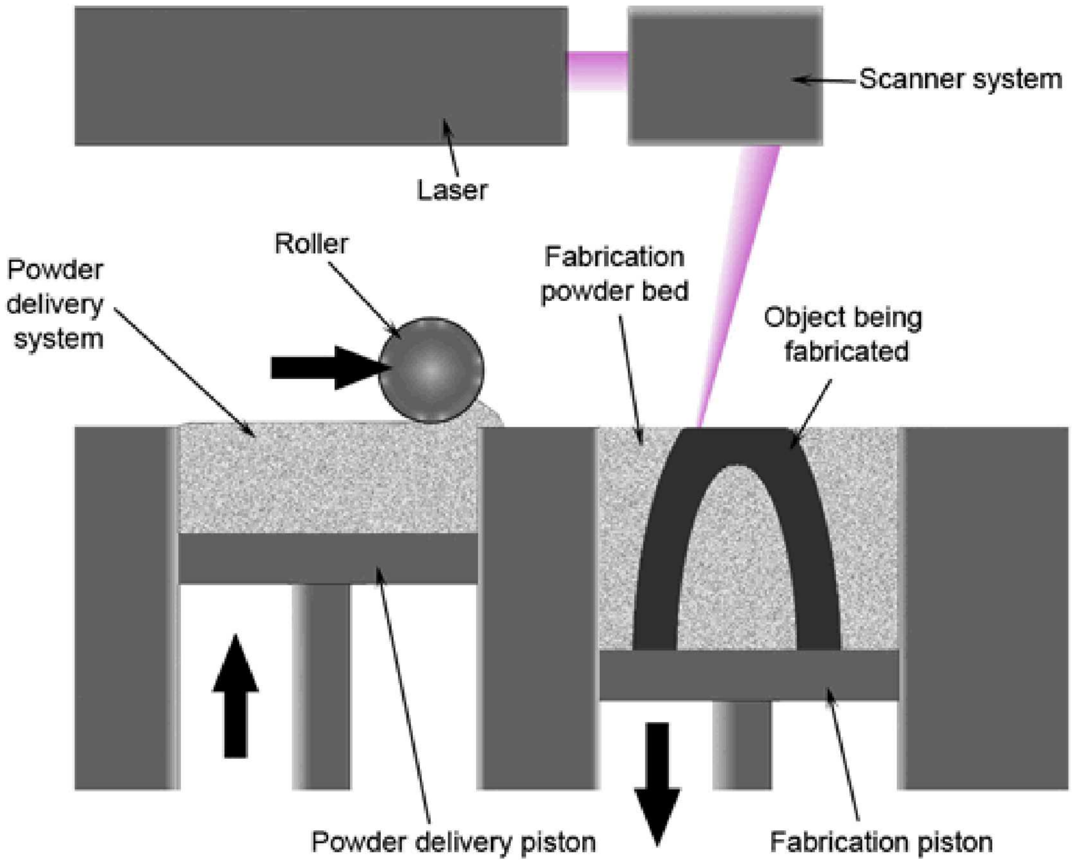


Image from: SPI Lasers

Direct Metal Laser Sintering (DMLS)

- Argon or nitrogen atmospheres
- Extreme thermal gradients resulting in residual stresses

Electron Beam Additive Manufacturing (EBAM)

- Similar to DMLS
- Uses an electron beam to pre-heat and melt metal powder
- Process occurs in a vacuum

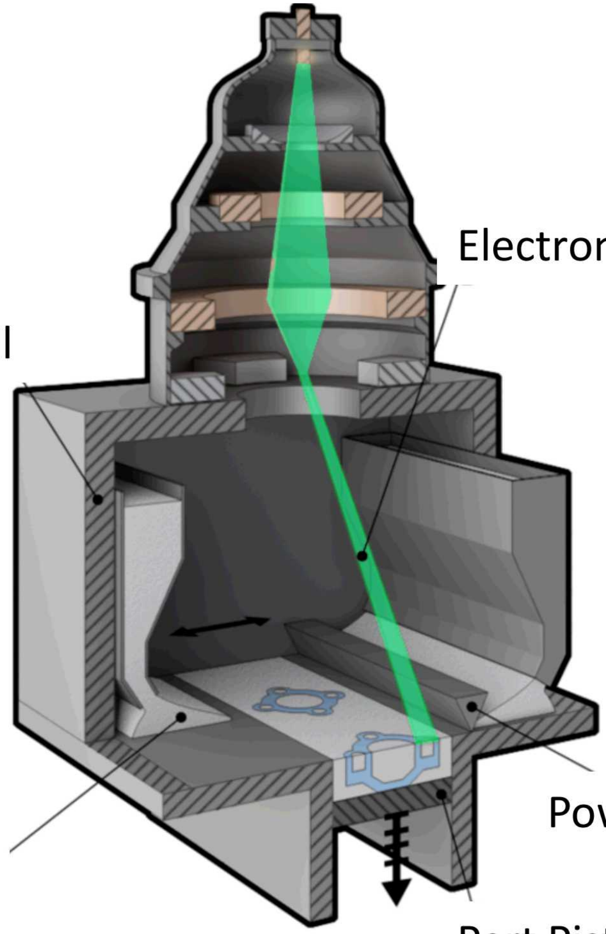


Image from: Manufacturing Guide

Laser Engineering Net Shaping (LENS)

- Directed energy deposition
- Powder feed around laser instead of powder bed
- Able to be coupled with CNC milling machine for dimensional and feature finishing

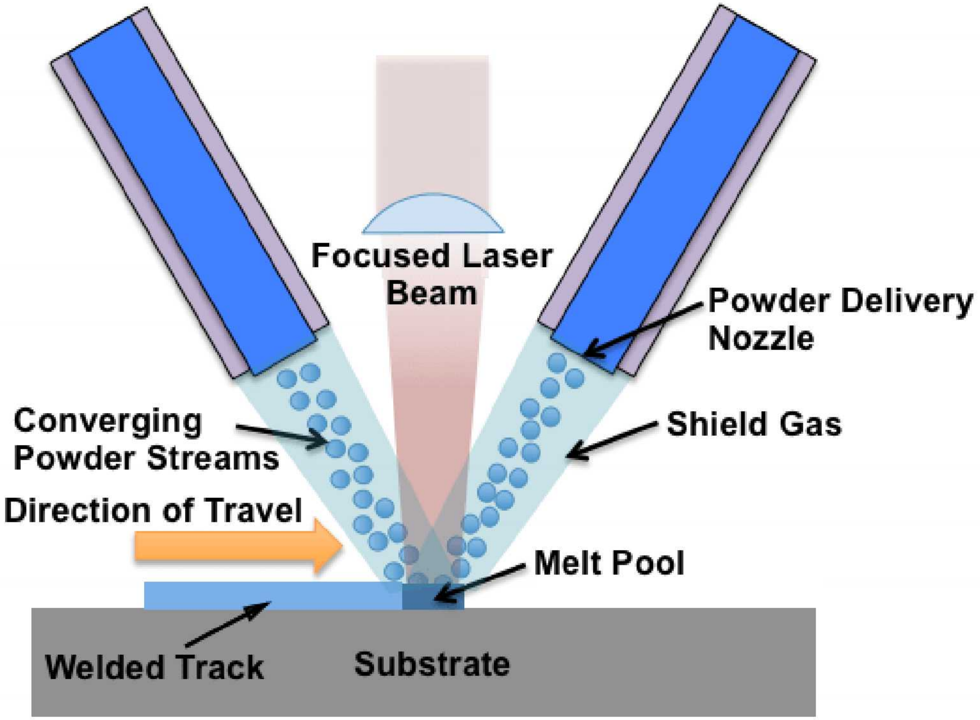


Image from: Bits into Atoms

Thermal Monitoring in AM

- Pre-heat in EBAM
- Melt pool measurements in DMLS and LENS
- Cooling rate monitoring in DMLS and LENS
- IR camera wavelength ranges
  - Short-wave: 1-3 microns
  - Mid-wave: 3-5 microns
  - Long-wave: 7.5-13 microns

Thermal Image of Build Surface in EBAM Machine after Beam Scanning has Occurred

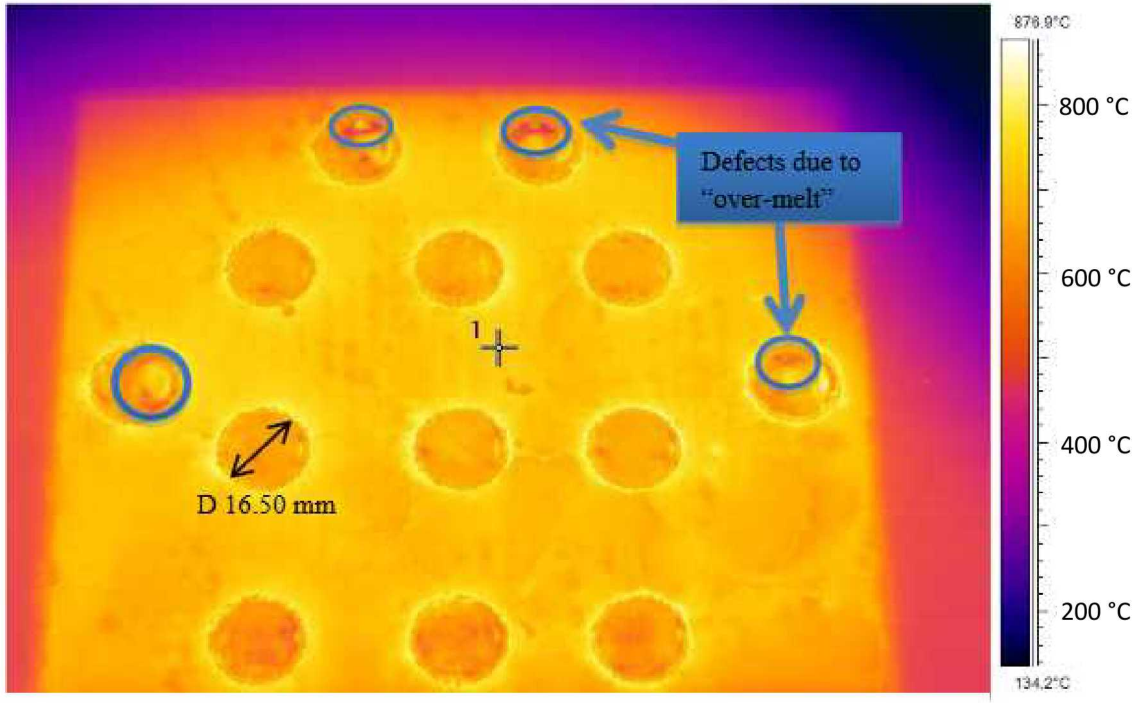
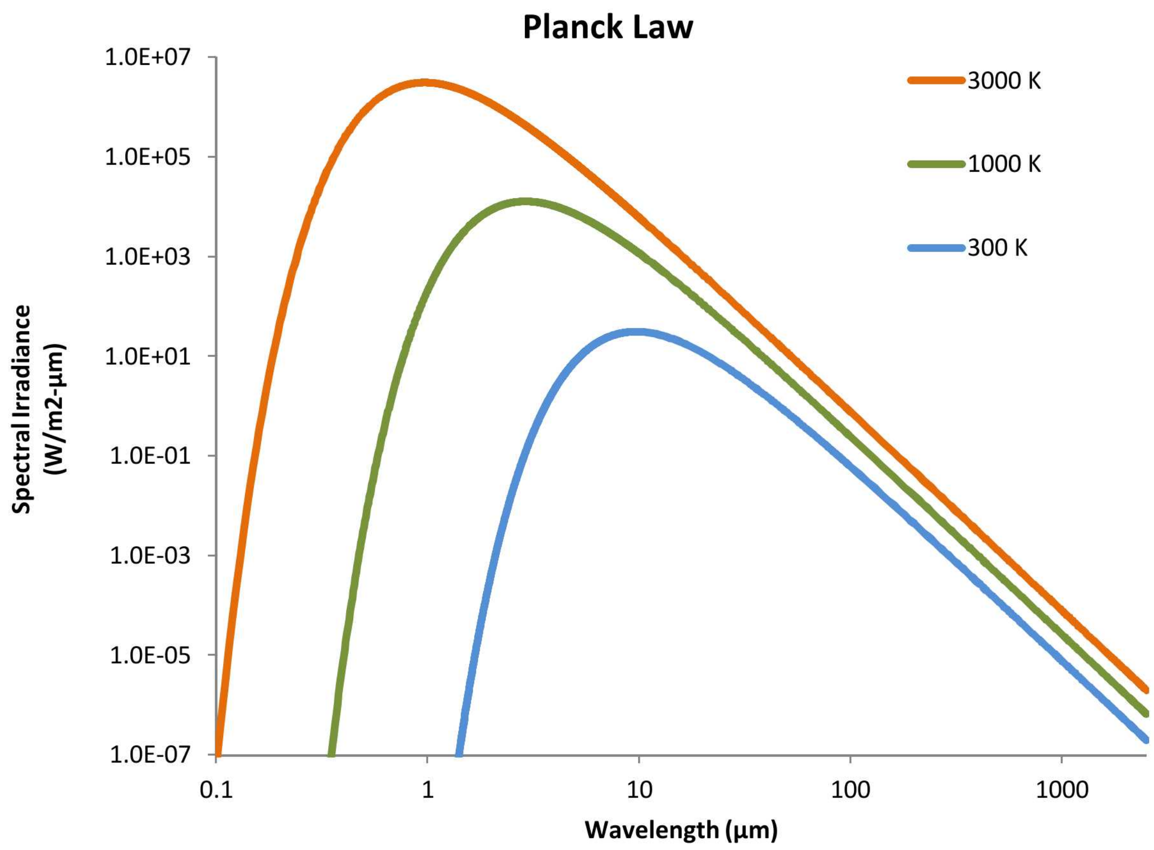


Image from: Rodriguez et al.

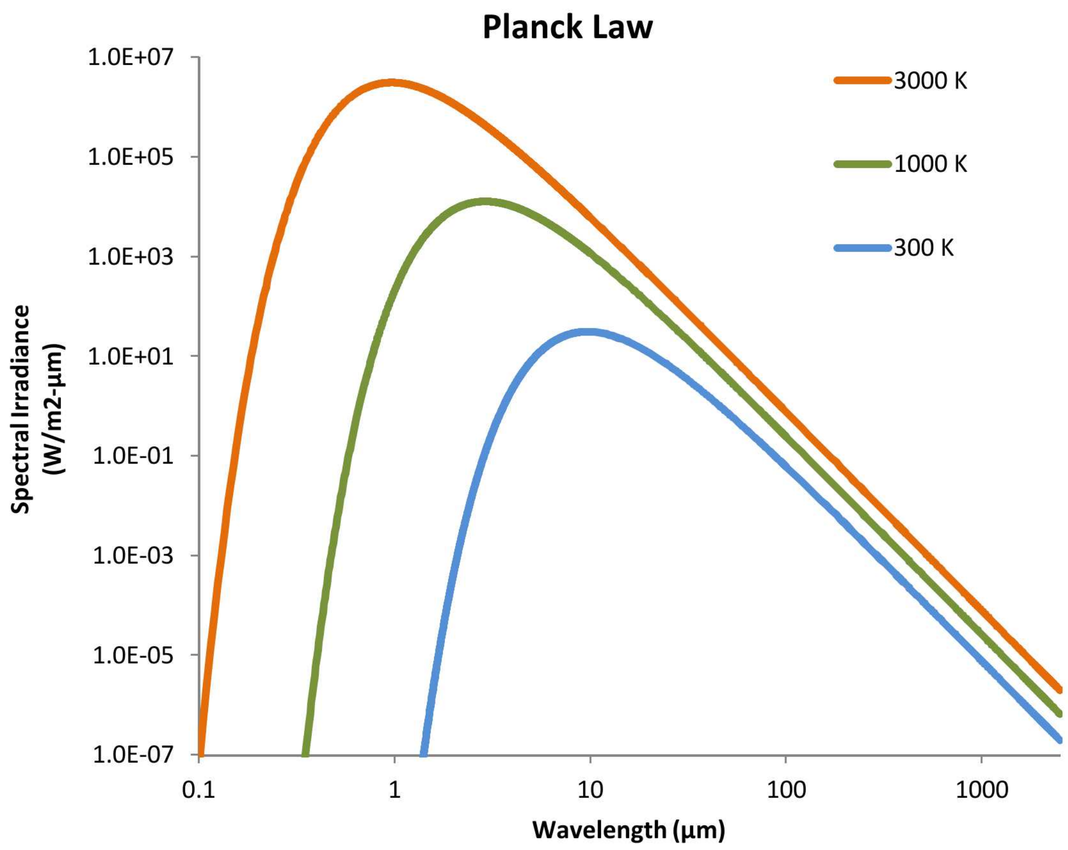
Radiation

- Black Body
- Stefan-Boltzmann Law
  - $E = \varepsilon\sigma T^4$
- Gray Body
- Emissivity
  - Material, wavelength, temperature, surface conditions



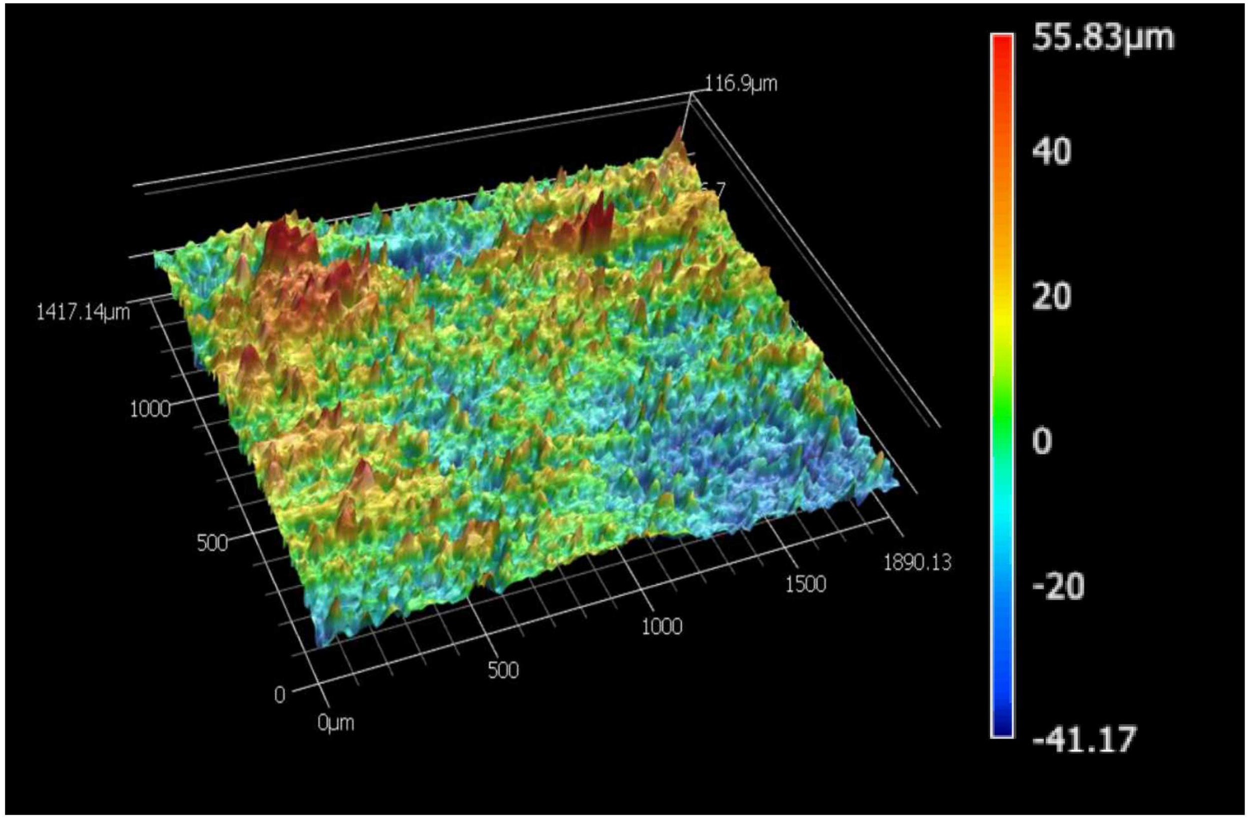
Radiation

- A + R + T = 1
  - A = Absorption
  - R = Reflection
  - T = Transmission
- Under thermal equilibrium conditions
  - Absorption = Emission

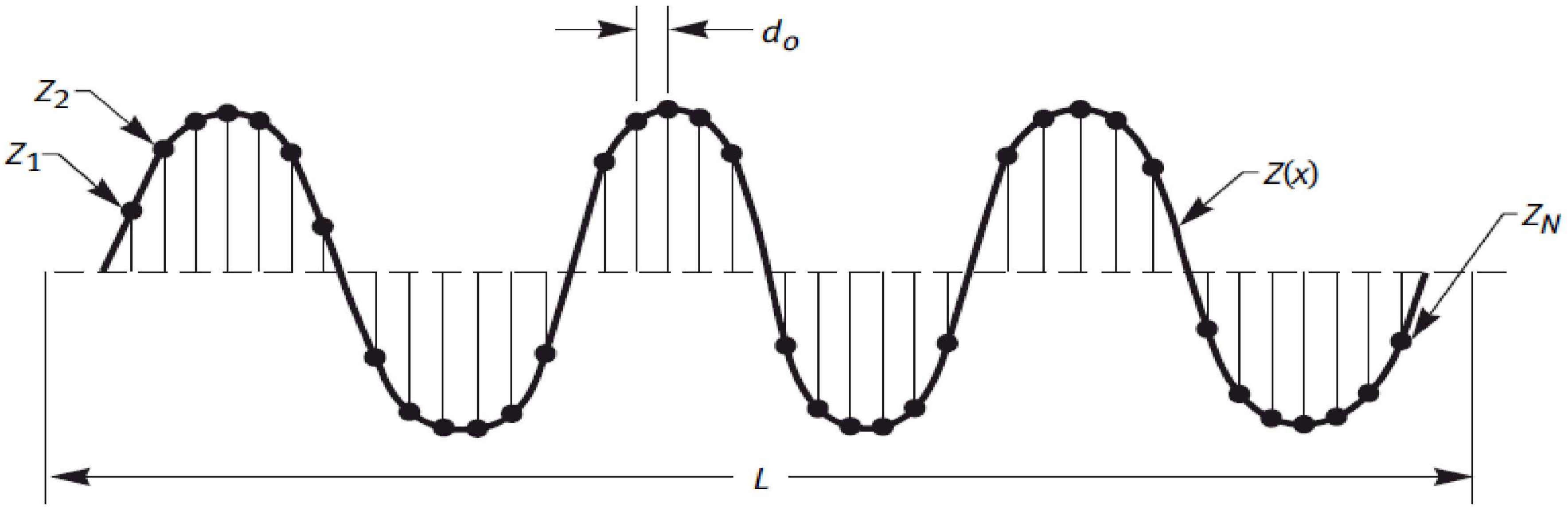


Surface Roughness

- ASME B46.1
- ISO 4287
- R_a is dominant in literature (90% of AM literature references this when discussing surface roughness)



Surface Roughness Definitions

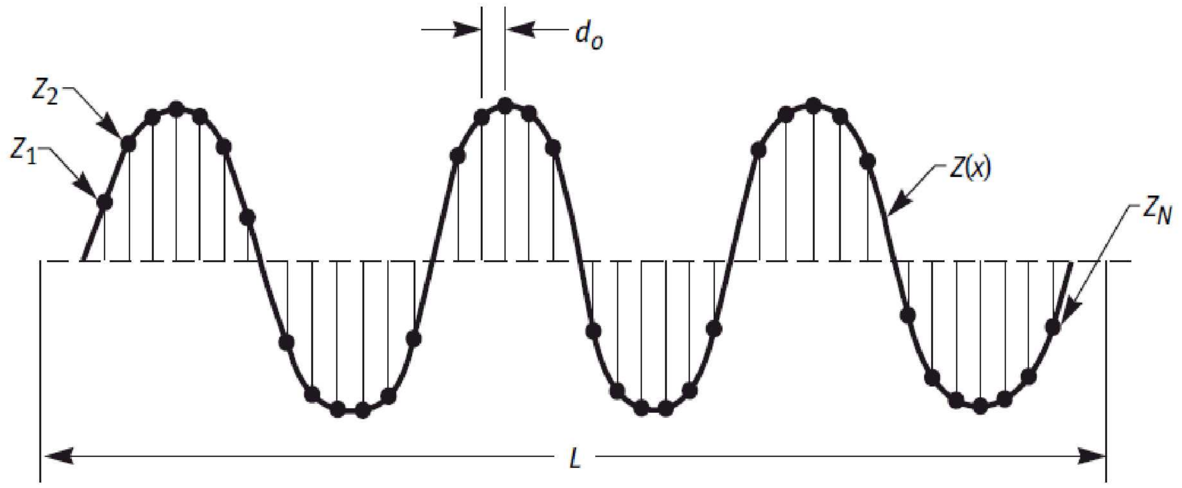


$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx \quad R_q = \sqrt{\frac{1}{L}\int_0^L Z(x)^2 dx} \quad R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ}{dx}\right)^2 dx} \quad R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|}dx$$

Sourced from: ASMBE B46.1

Arithmetic Mean Roughness

- Used in over 90% of AM literature to describe surface roughness
- Common parameter for traditional manufacturing as well
- Suggested as being insufficient as a delineator between different AM surfaces



$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx$$

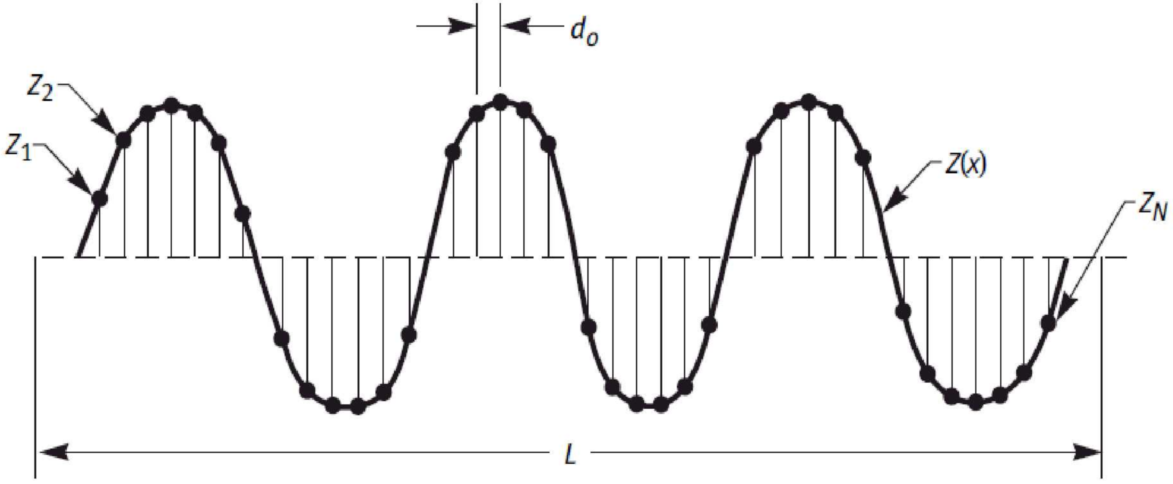
$$S_a = \frac{1}{A}\int_0^{L_y}\int_0^{L_x} |Z(x,y)|dxdy$$

Sourced from: ASMBE B46.1

Root Mean Square Roughness

- Common parameter used to describe surface roughness in both AM and traditional manufacturing

- Used in optical literature as the reference number for surface roughness



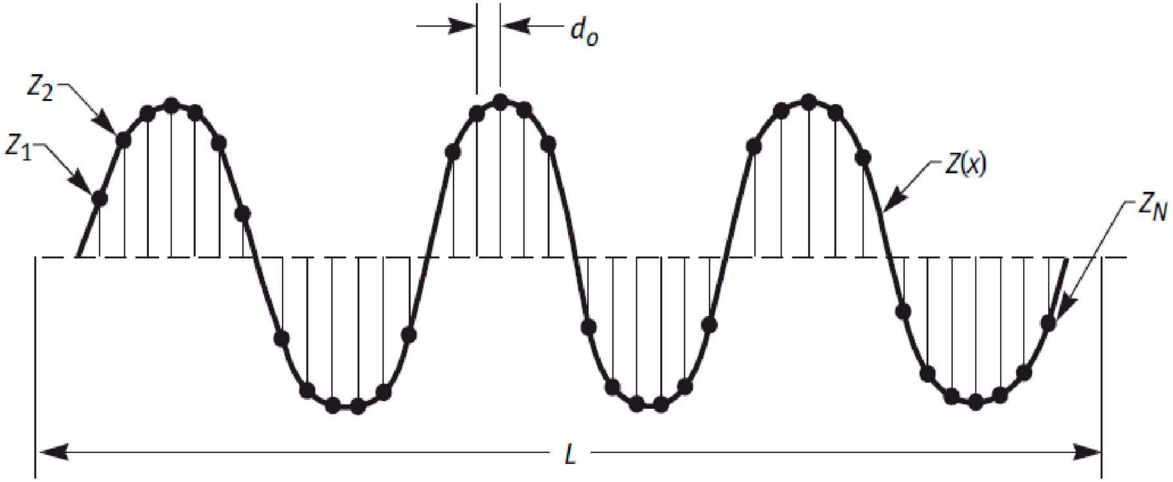
$$R_q = \sqrt{\frac{1}{L}\int_0^L Z(x)^2 dx}$$

Sourced from: ASMBE B46.1

Root Mean Square Slope

- Suggested to be a better delineator of different AM surfaces

- Optical literature suggested slope of the surface may be related to emissivity trends



$$R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ}{dx}\right)^2 dx}$$

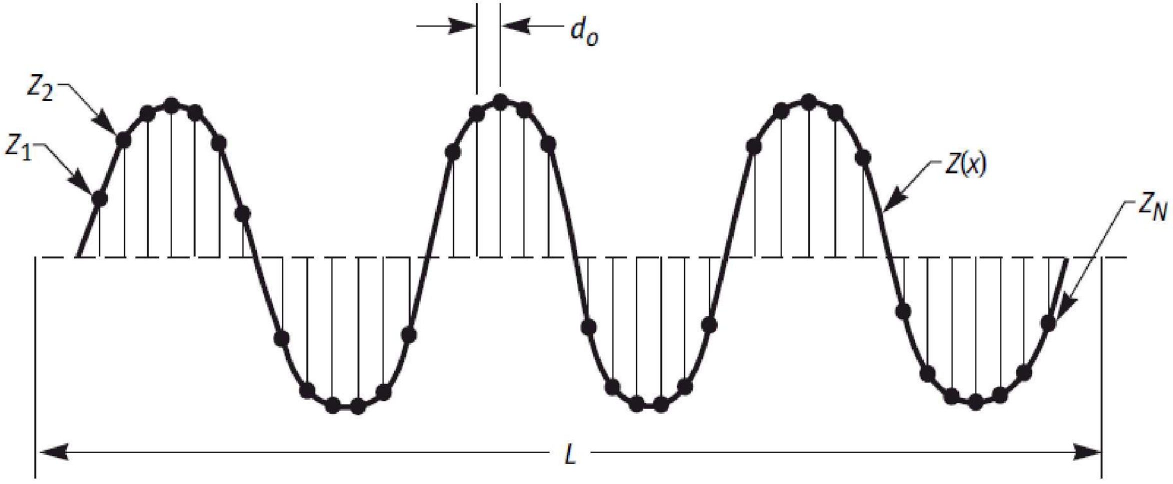
$$S\Delta q = \sqrt{\frac{1}{A}\int_0^{L_y}\int_0^{L_x} \left(\frac{dZ(x,y)}{dx}\right)^2 + \left(\frac{dZ(x,y)}{dy}\right)^2 dxdy}$$

Sourced from: ASMBE B46.1

Arithmetic Tilt Angle

- Optical literature suggested slope of the surface may be related to emissivity trends

- Will be used to describe emissivity trends later on



$$R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|}\,dx$$

Sourced from: ASMBE B46.1

Surface Roughness in AM

- Top surface is the focus since that is what is visible for in-situ monitoring techniques
- Shear forces in melt pool create ripple effect which is then frozen due to high processing speeds
- Balling
  - Laser power too high causing currents where outward forces exceed surface tension in melt pool and material is ejected
  - Raleigh Instability: scan speed too fast compared to laser power so balling occurs due to long melt pool breaking up

Surface Roughness Relationship with Emissivity

Case 1: $R_q/\lambda << 1$

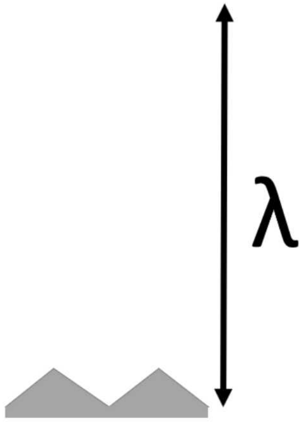
- Optically smooth surface, where the roughness of the surface does not contribute to the thermal emissivity of the object.

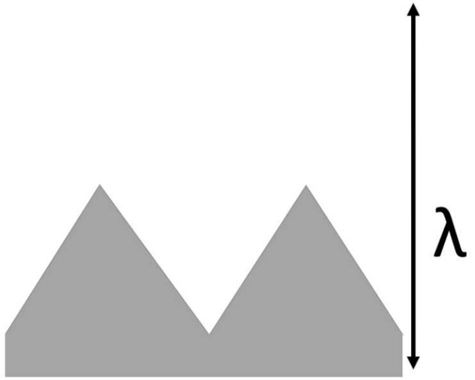
Case 2: $0.2 < R_q/\lambda < 1$

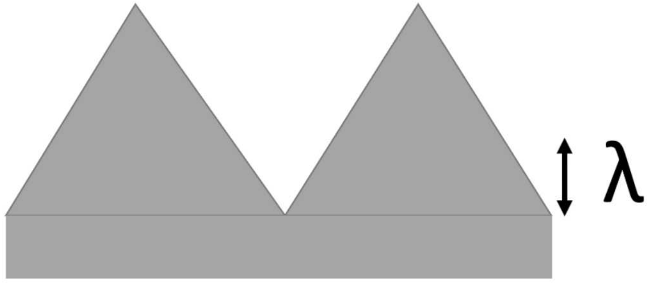
- Intermediate region where there is no easy defined relationship between emissivity and surface roughness. The roughness of the surface does contribute but is not solely responsible for affecting the emissivity.

Case 3: $1 < R_q/\lambda$

- The geometric region, where it is suggested that the slope of the peaks and valleys of the surface can play a key role in emissivity trends.







Sourced from: Wen and Mudawar, “Modeling the Effects of Surface Roughness on the Emissivity of Aluminum Alloys”

Problem Statement

- Emissivity can be affected by extremely rough surfaces
  - Additive manufacturing has large values and ranges of surface roughness
  - Wavelengths used for monitoring are at same length scales as surface roughness of additive parts
- Accuracy of thermal monitoring is paramount for quality control of parts
  - Cool down measurements when material has solidified is key in determining materials properties

Research Plan

Task 1: Defining surface parameter(s) that affect thermal emissivity

Task 2: Investigate effects view angle has on emissivity changes caused by vary surface roughness

Task 3: Select and test in-situ surface texture measurement for the purpose of in build adjustment of emissivity for thermal monitoring instruments

First Task: Define Surface parameter(s) that affects emissivity

- Simulation Work
  - Model basic surface features to discover what geometric characteristics are affecting emissivity
  - Discover phenomena behind emissivity trends
- Experimental Measurements
  - Fabricate metallic AM sample with a range of SR
  - Correlate measured surface roughness with measured emissivity
  - Discover which new and pre-existing surface roughness parameters best describe emissivity behavior

Simulation Strategy – Lumerical FDTD

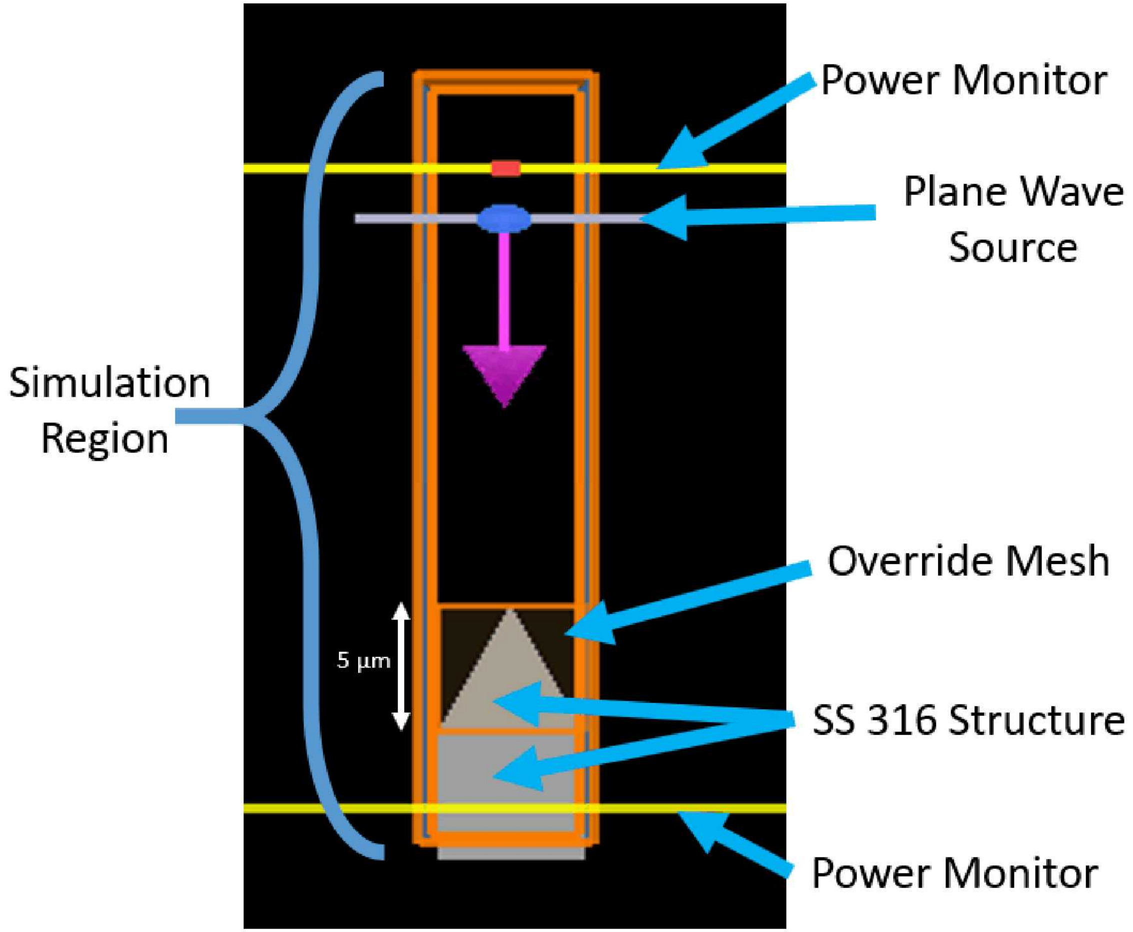
- Finite Difference Time Domain (FDTD)
  - Calculates electric and magnetic fields at different time steps
- Maxwell solver
  - Electric field, magnetic field, electric flux, and magnetic flux are calculated for Yee Cell (fundamental spatial unit)
- Chosen over ray tracing due to surface features on same length scale as light wavelength range
  - Ray tracing may not accurately capture all optical behavior

Simulation Strategy

- Basic 2D periodic geometries were chosen for initial simulations
  - Less computation time and memory requirements
  - Geometries chosen to observe effects of certain SR parameters and various characteristics of surface topography
- Parameter sweeps
- Wavelength Range: 1-14 microns
- Material – 304 Stainless Steel

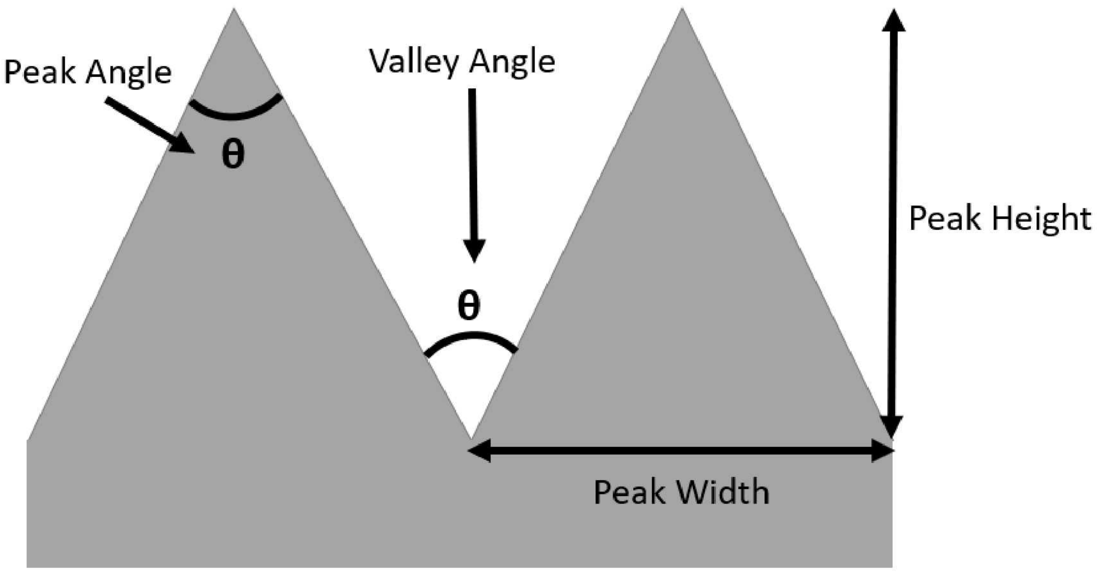
Overall Simulation Set Up

- 2D geometry (z plane goes to infinity)
- X axis boundary conditions: periodic
- Y axis boundary conditions: perfectly matched layer (PML)
- Plane wave source
- Power monitors above and below surface to measure reflection and transmission
- Mesh size: .1 microns
  - Didn't gain significant accuracy when using smaller sizes



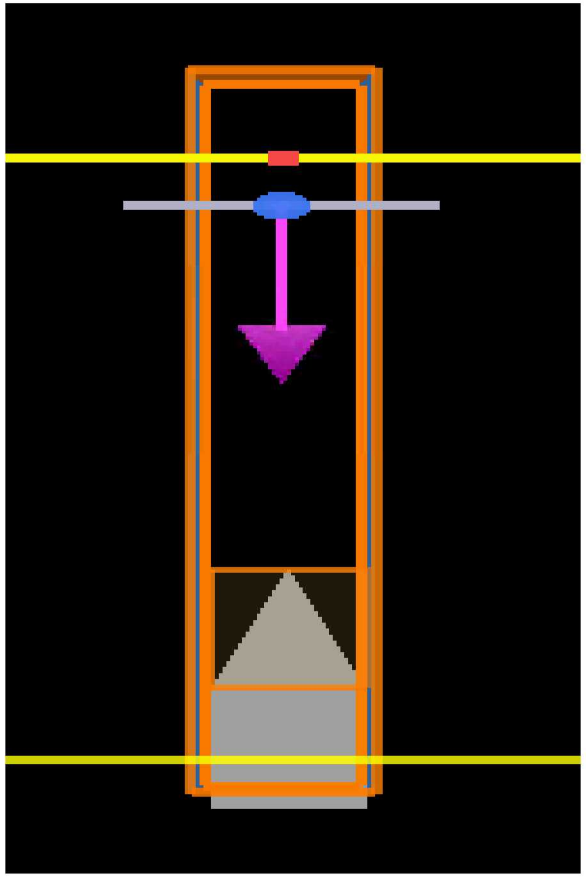
Simulation Surface Roughness Exploration

- Looked into existing SR parameters' ability to describe emissivity trends
  - R_a and RΔq
  - Suggested in previous literature
- Looked at new surface roughness measurements
  - Peak or Valley
    - Height
    - Width
    - Angle

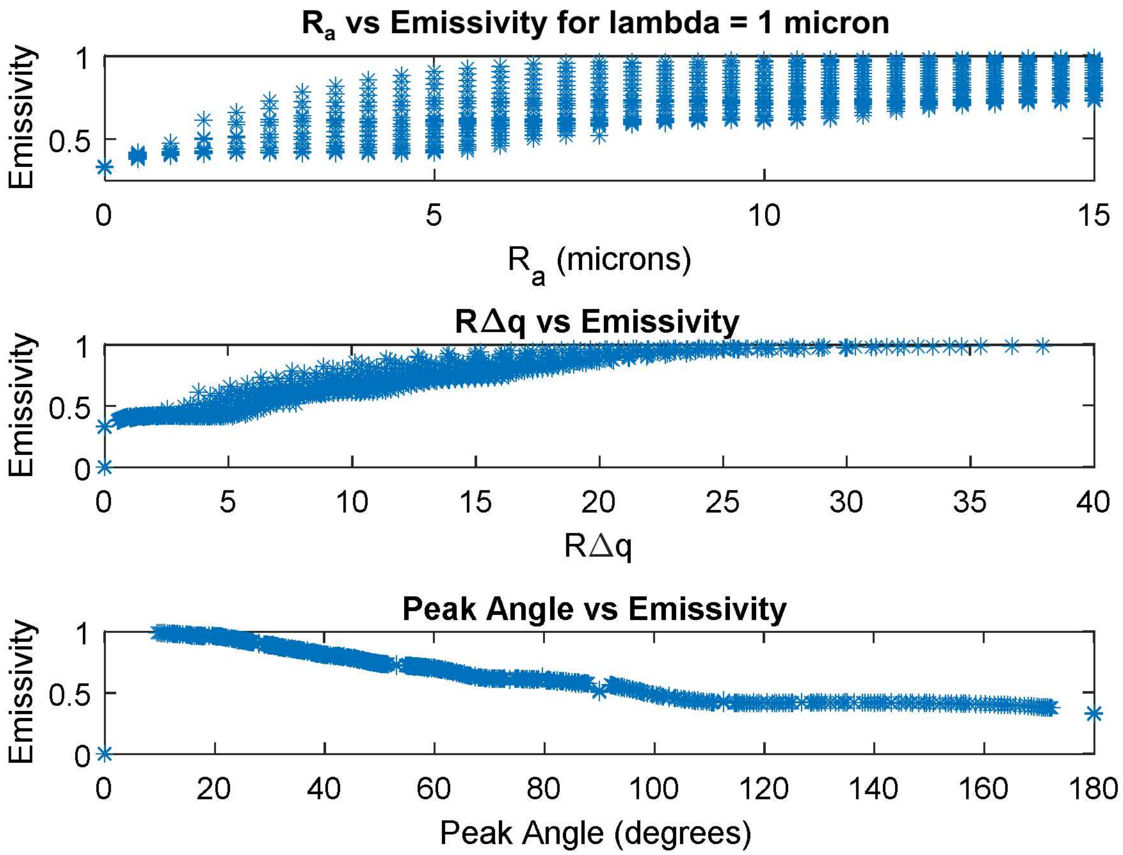


2D Triangle Set Up

- Isosceles Triangle
- Periodic Boundaries
- Variables
  - Height of triangle: 0-30 microns
  - Width of Triangle: 1-30 microns



2D Triangle Results



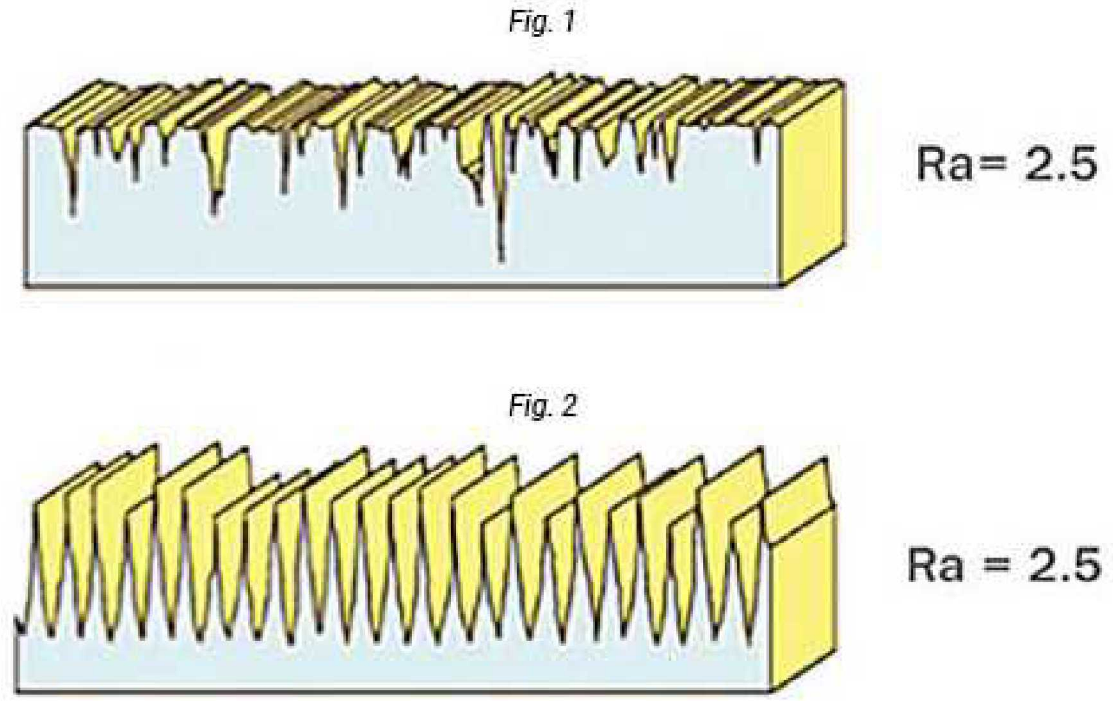
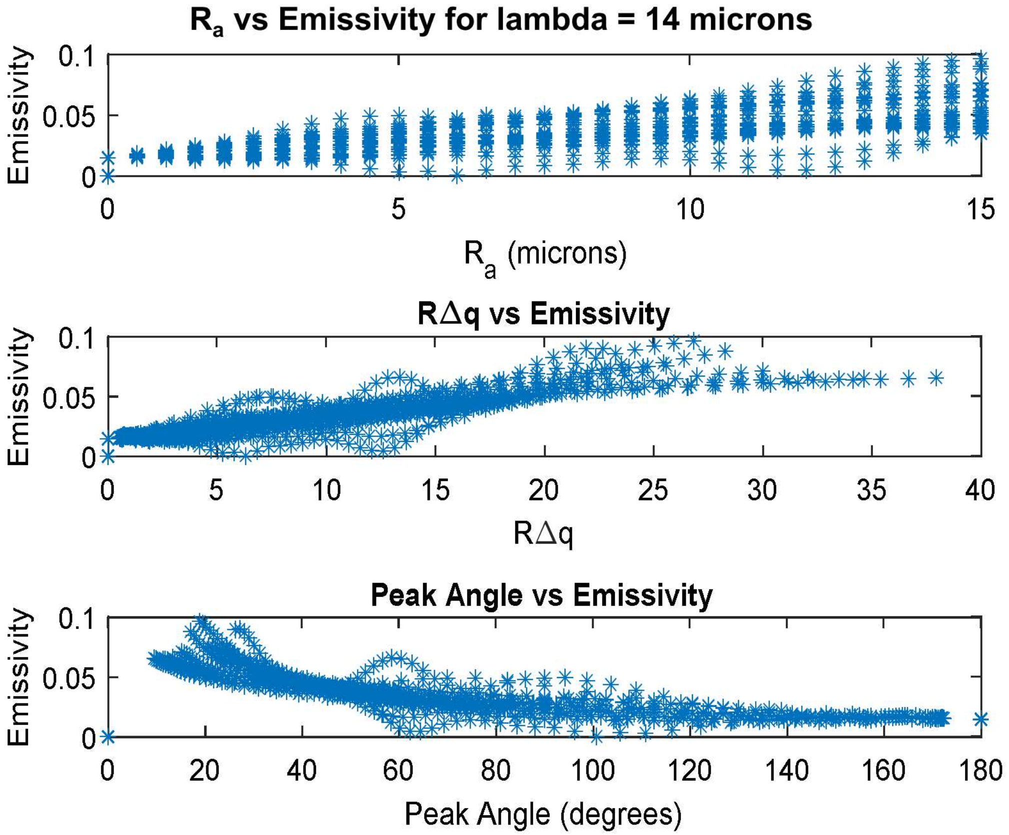


Image from: https://fluidpowerjournal.com/beyond-ra-surface-finish-matters-seal-performance/

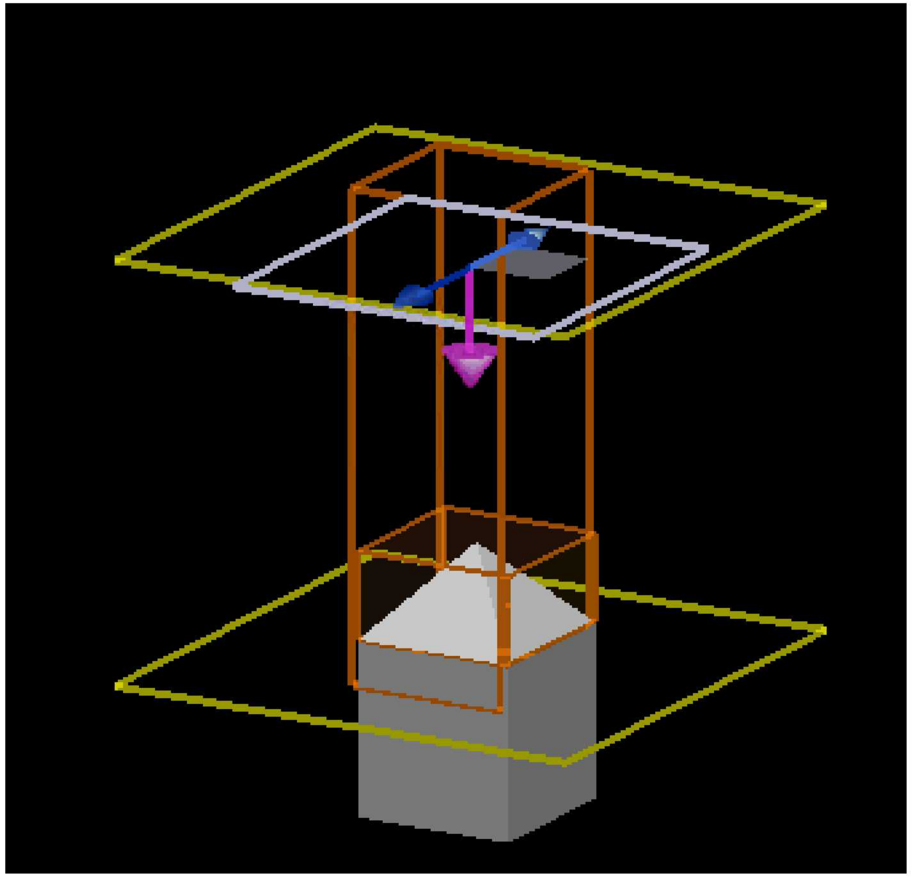
2D Triangle Results

- As observation wavelength increases, trends fall apart
- Ratio of R_q/λ falls below 1
  - Intermediate optical region
  - Emissivity not dominantly dependent on surface roughness

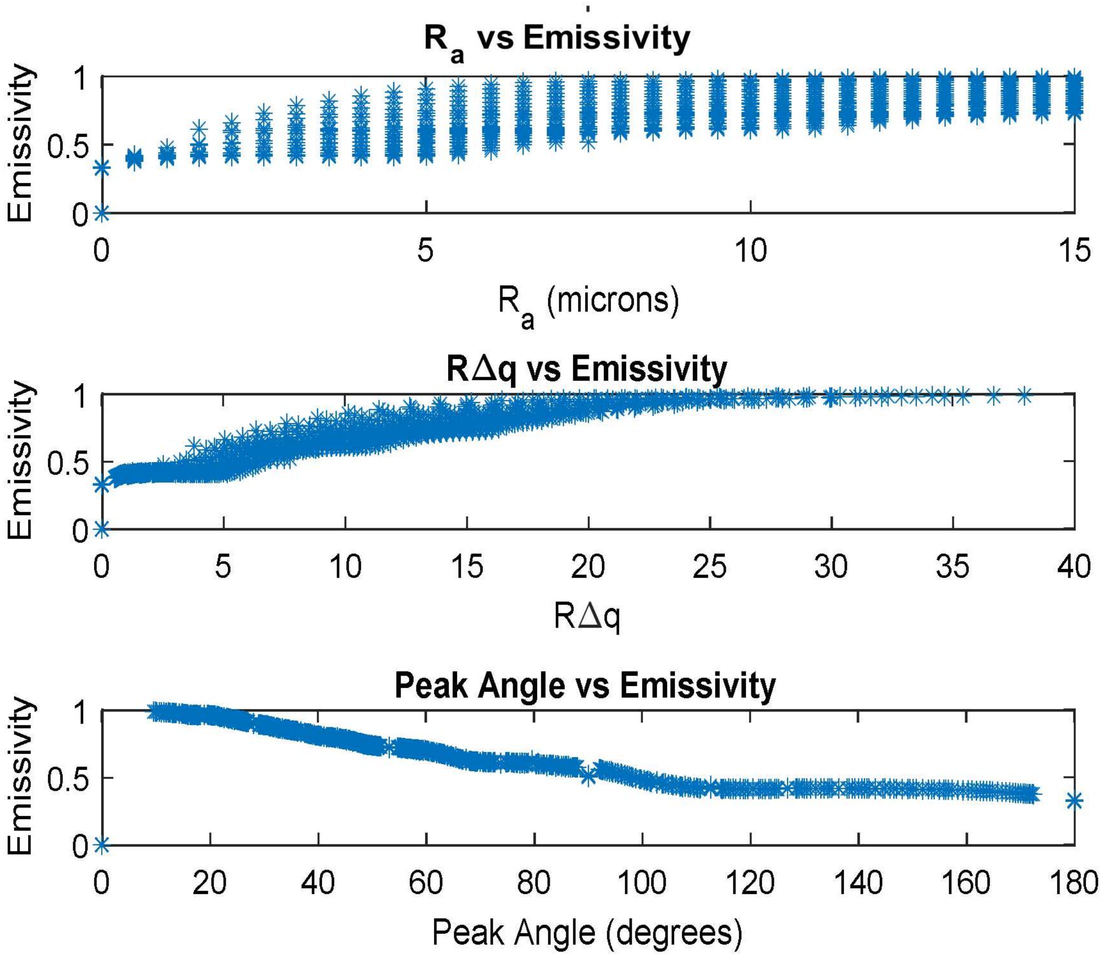


3D Pyramid Set Up

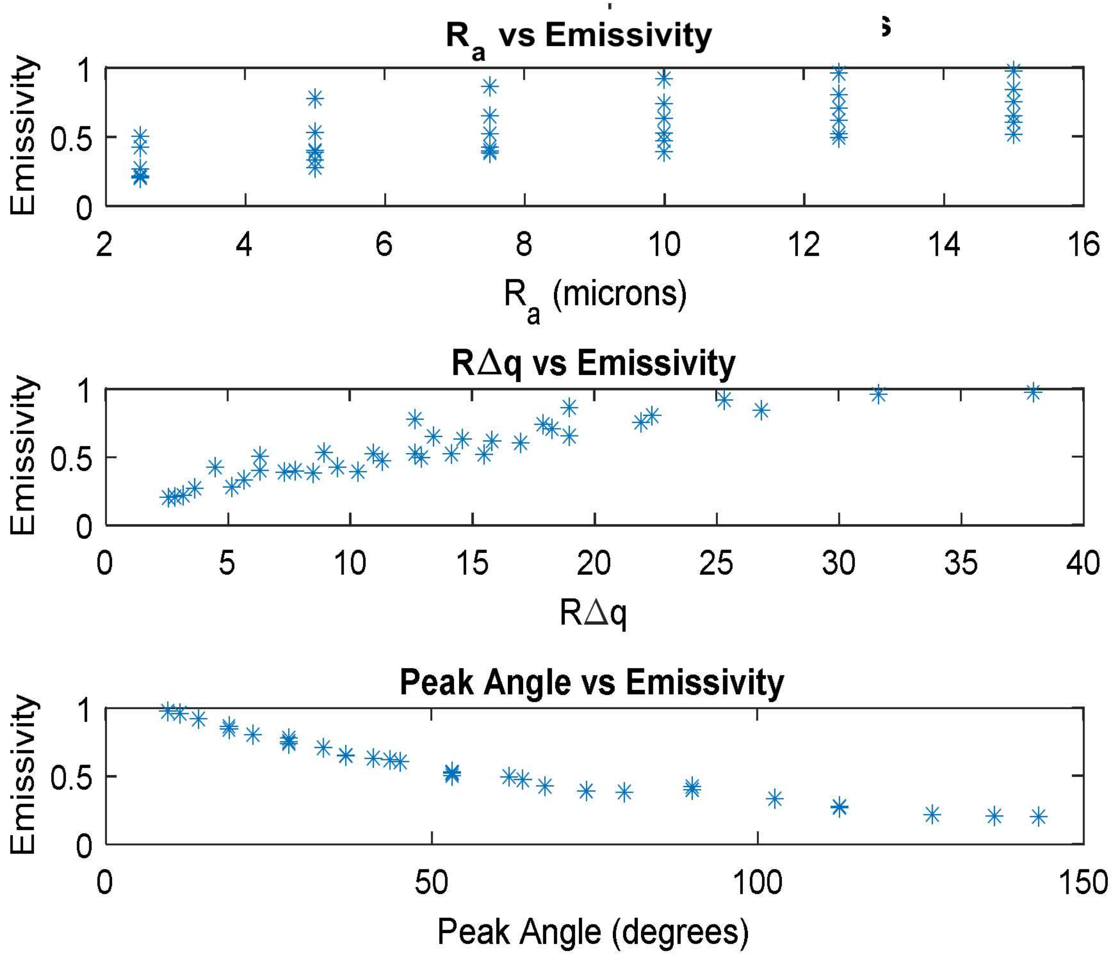
- 3D pyramid with identical geometry to 2D periodic triangle
- Periodic Boundaries
- Symmetry assumption used to reduce simulation space
- Variables
  - Height of pyramid: 5-30 microns
  - Width of pyramid: 5-30 microns



2D Triangle (676 simulations)

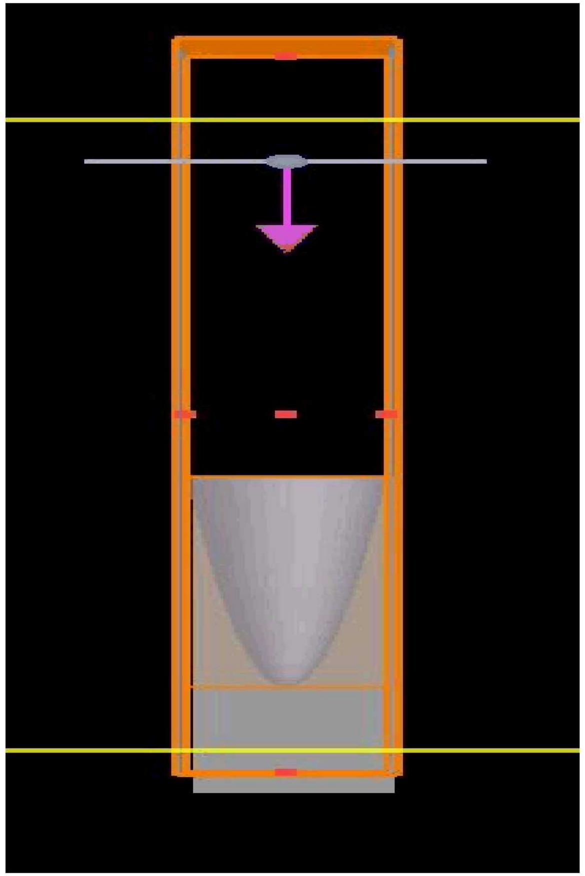


3D Pyramid (36 simulations)

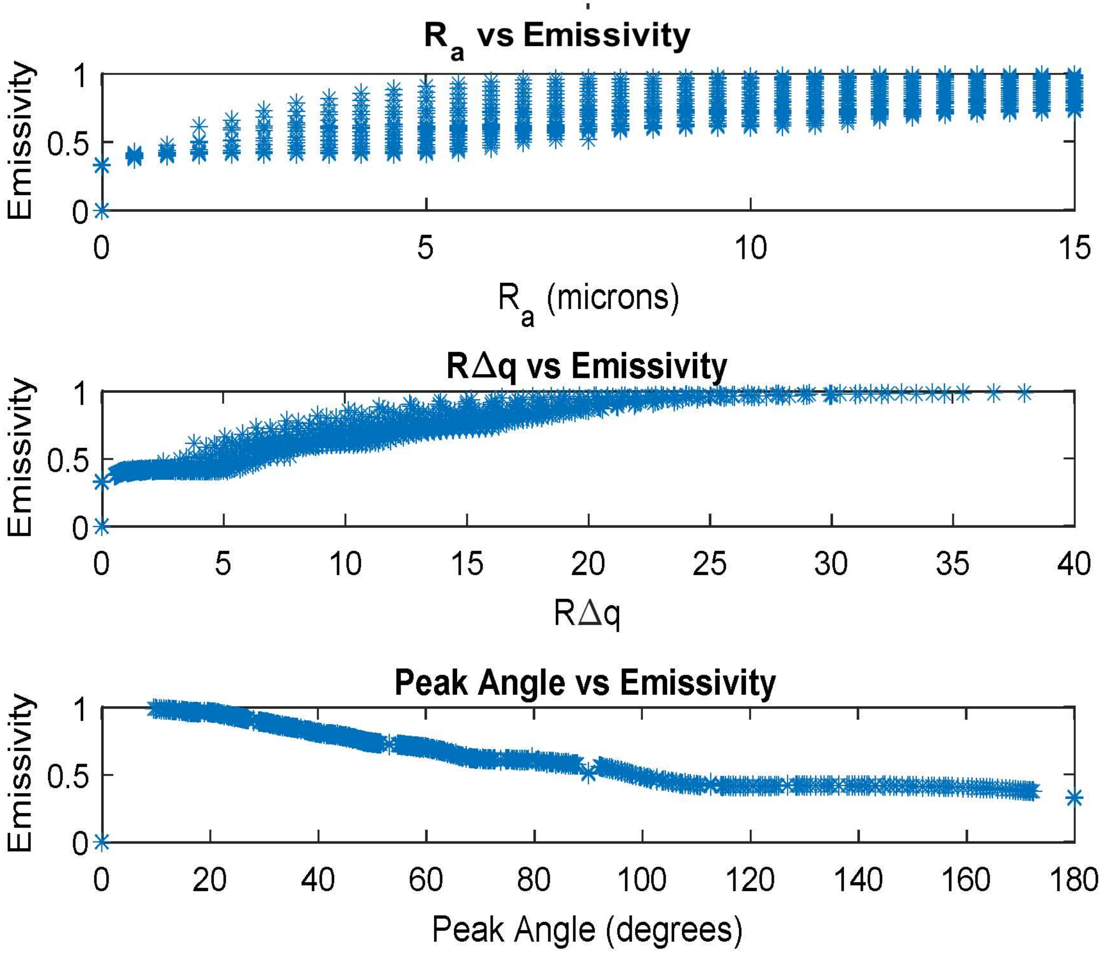


Parabolic Valley Set Up

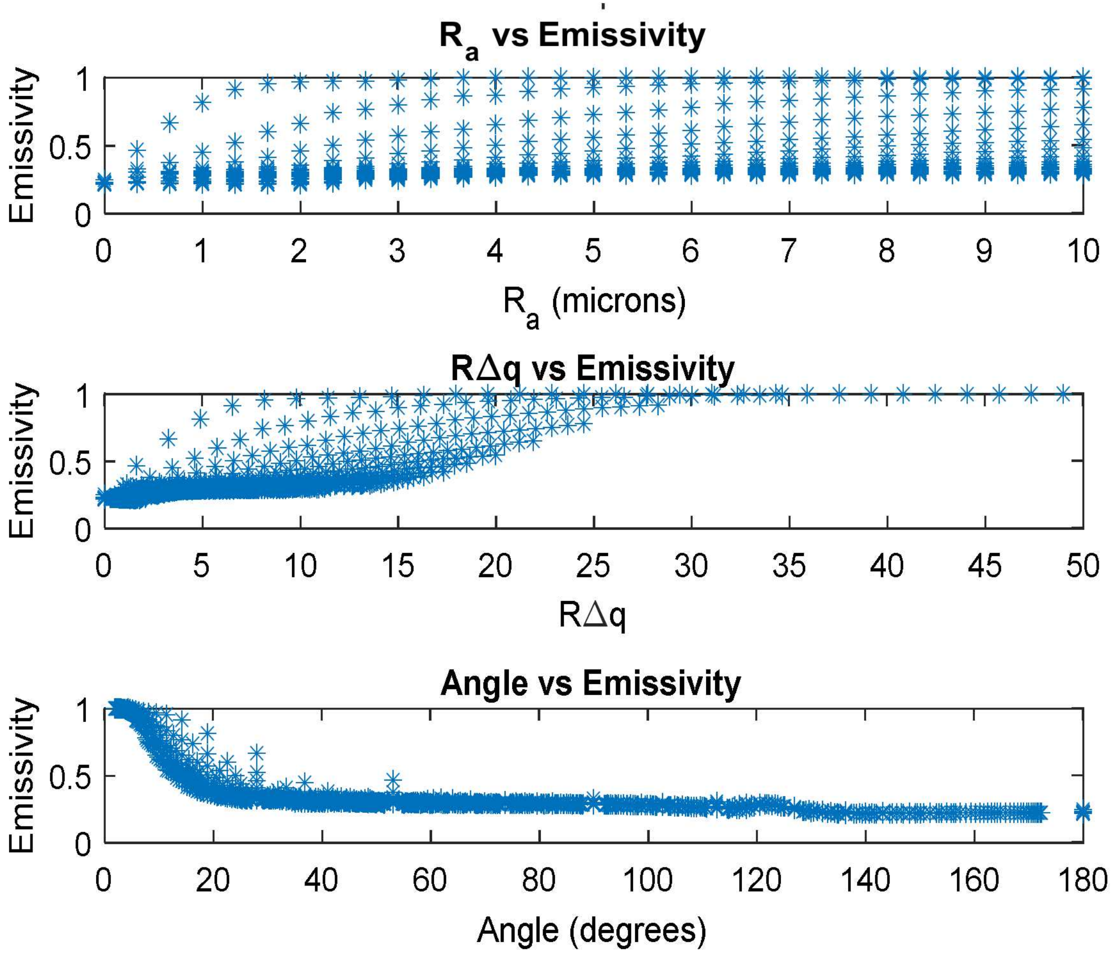
- Similar dimensions to triangle
- Periodic Boundaries
- Observe effects of more life-like surface shape
- Variables
  - Height of valley: 5-30 microns
  - Width of valley: 5-30 microns



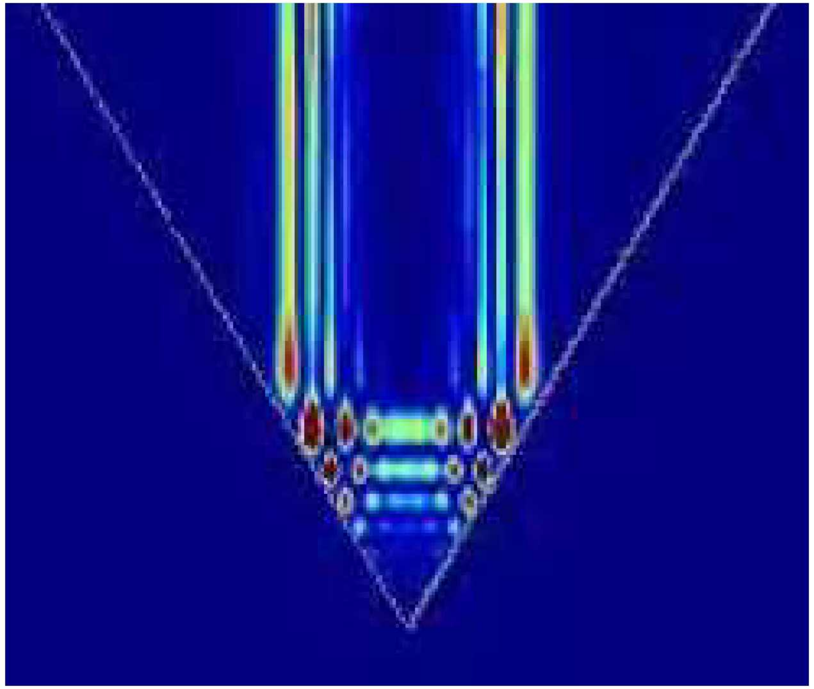
2D Triangle

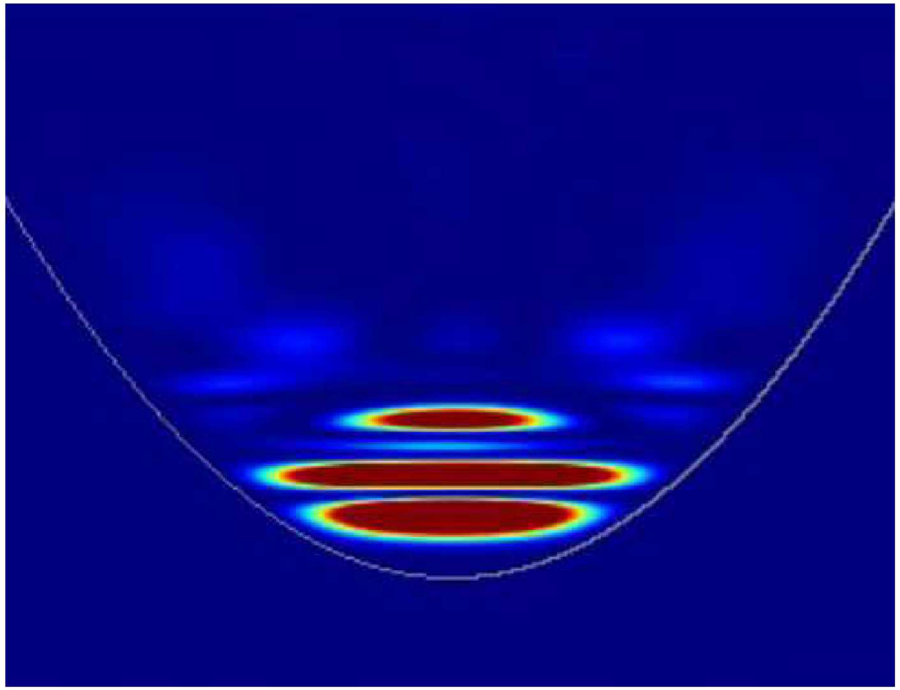


Parabolic Valley



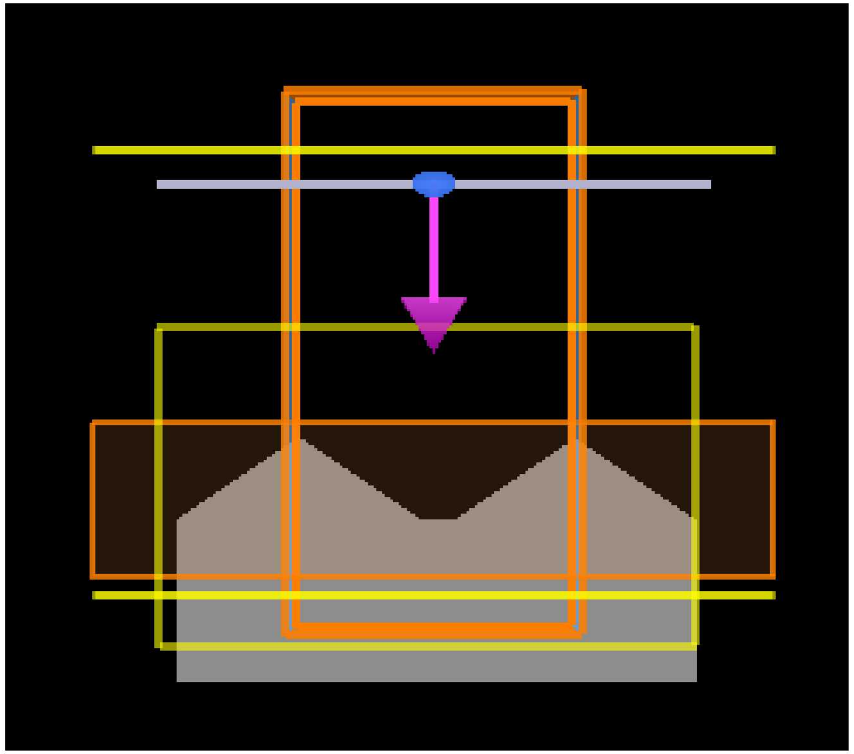
Triangular vs Parabolic Valley



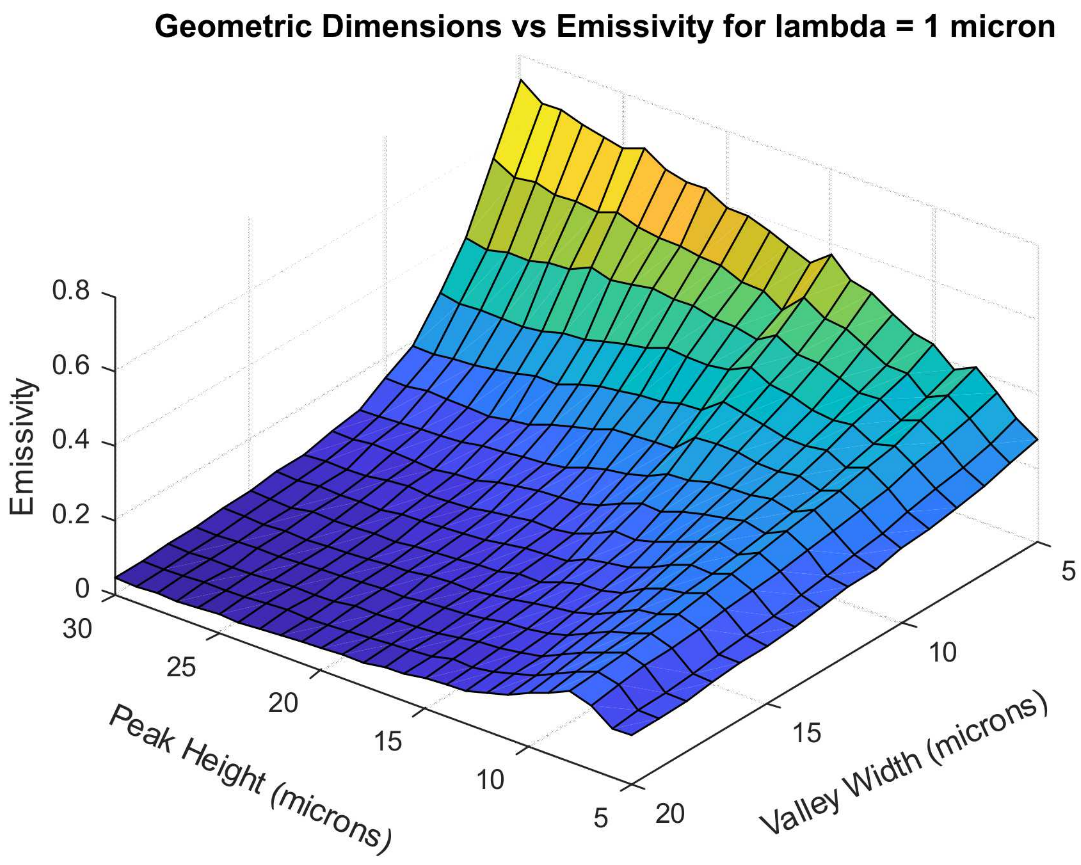


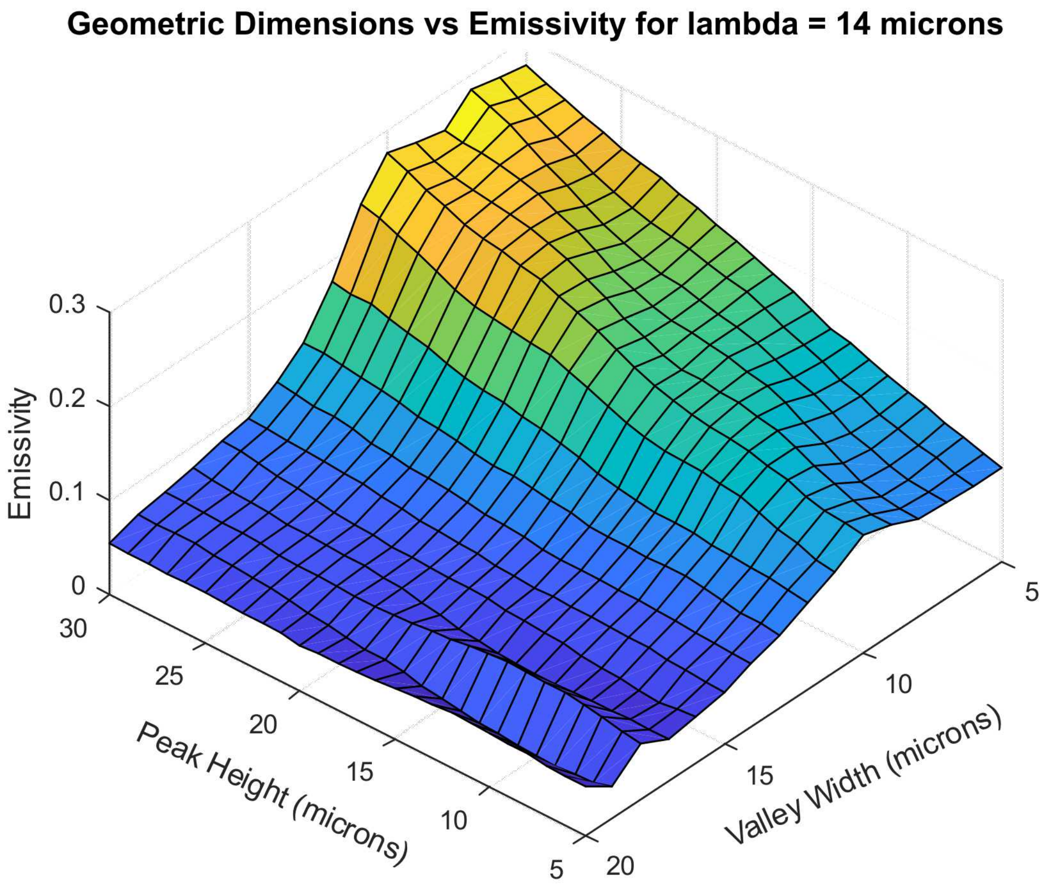
Flat Valley Set Up

- 2 isosceles triangle + flat valley in between
- Periodic Boundaries
- Variables
  - Height of triangles: 5-30 microns
  - Valley width: 5-20 microns



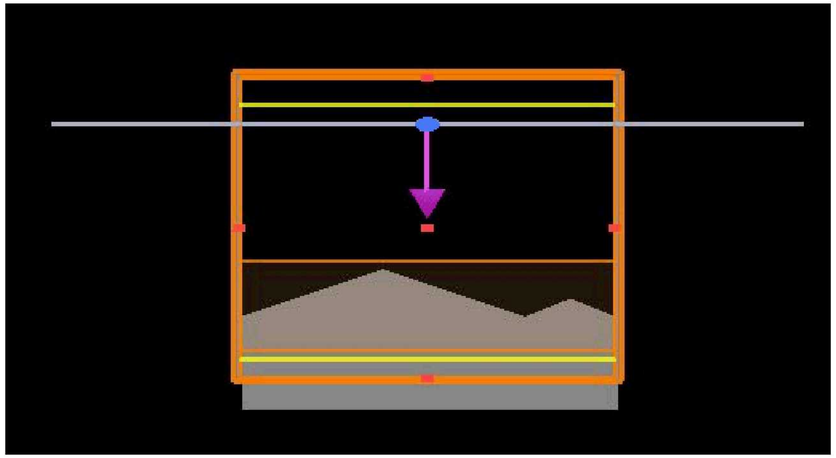
Flat Valley Results

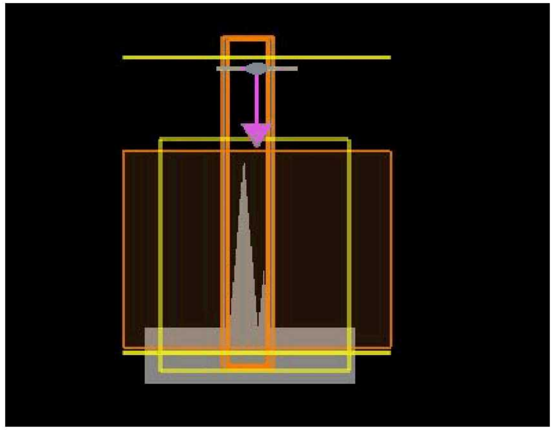




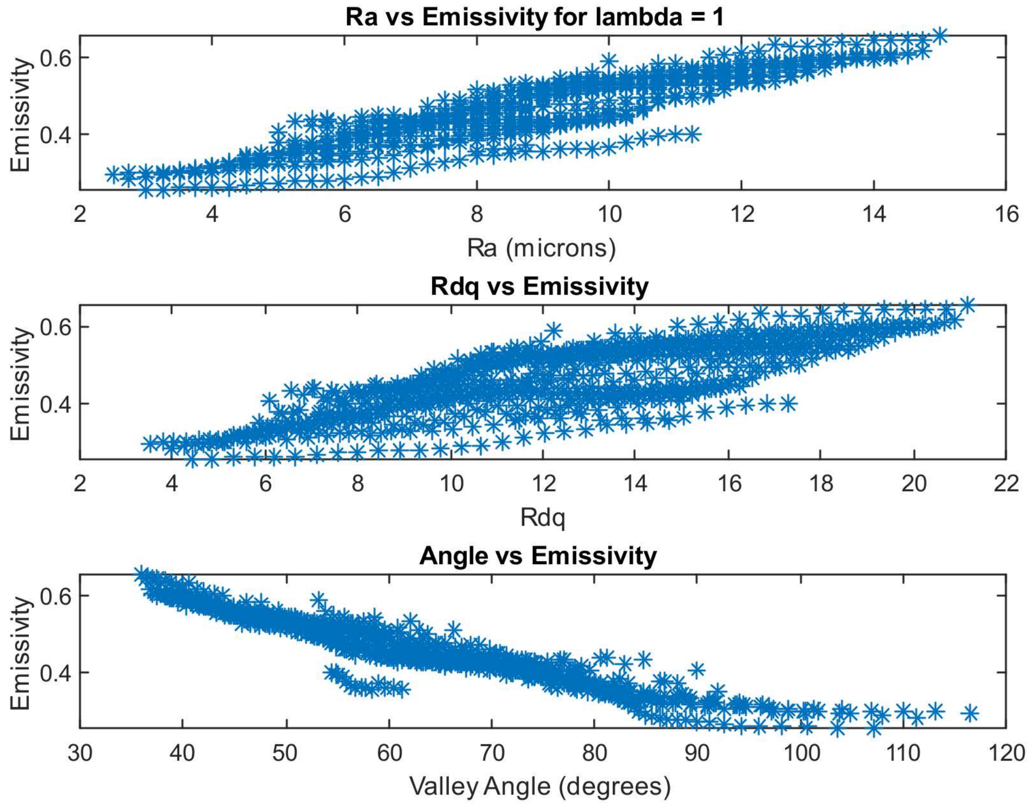
Multi-Sized Triangle Set Up

- 2 isosceles triangle with difference heights and widths
- Periodic Boundaries
- Variables (Height or Width)
  - Large triangle: 5-30 microns
  - Small triangle: 5-30 microns
  - Constant Width/Height
    - Small triangle: 10 microns
    - Large triangle: 10 microns

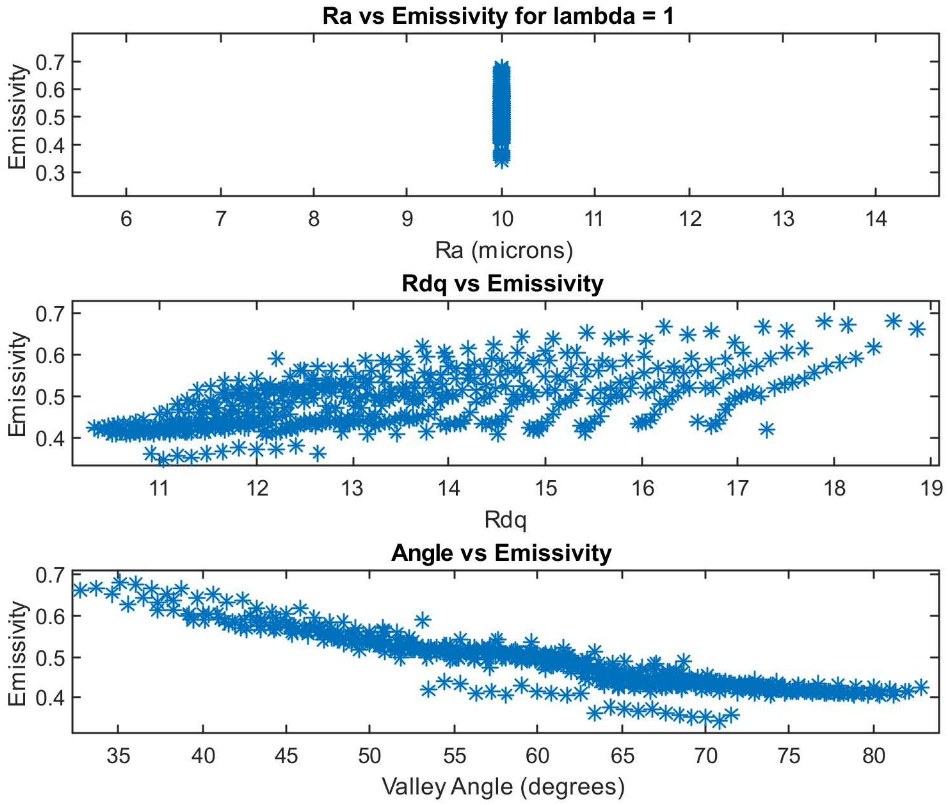




Height Change

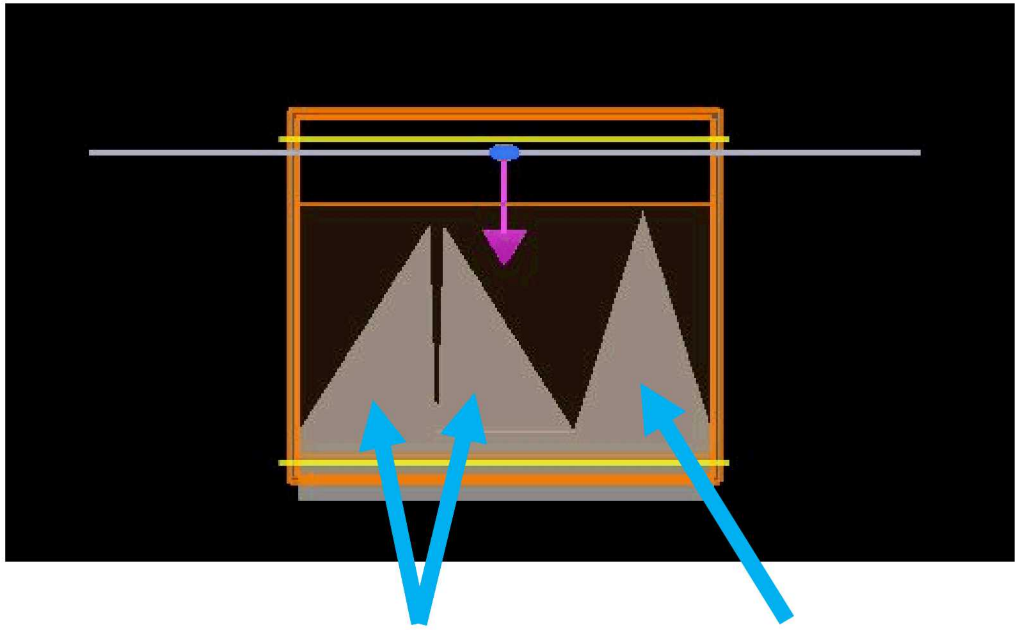


Width Change

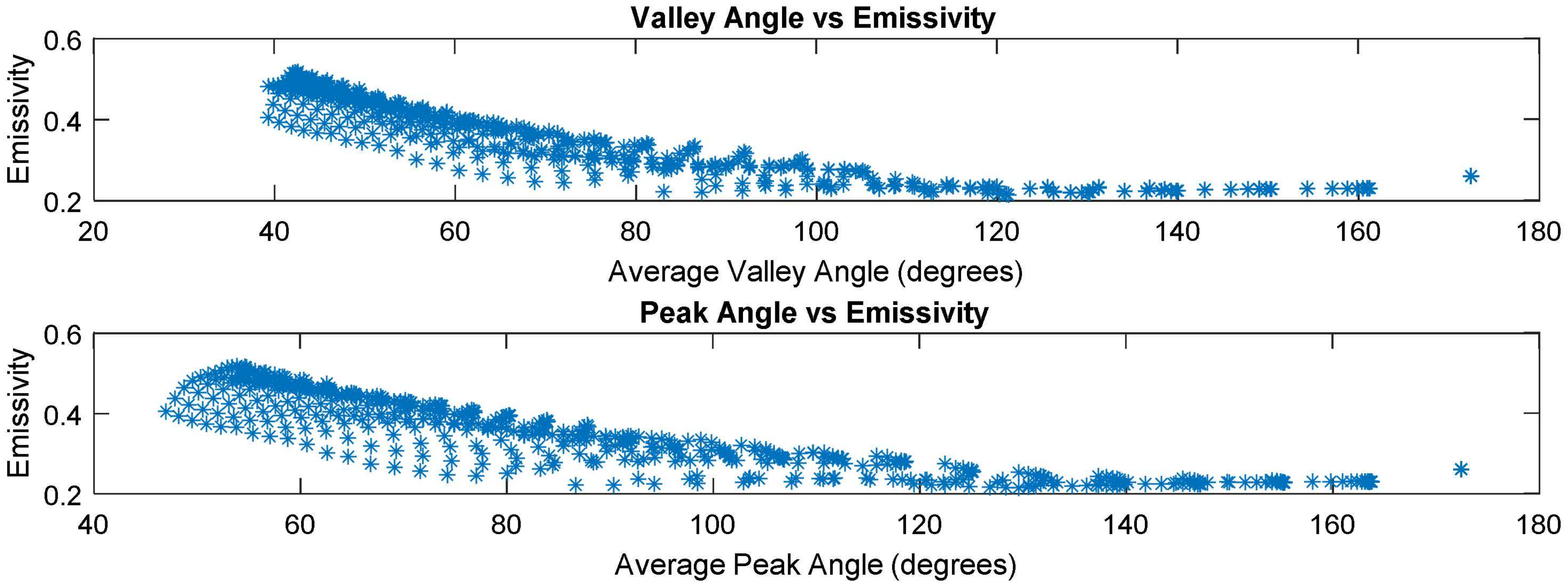


Skewed Triangle Set Up

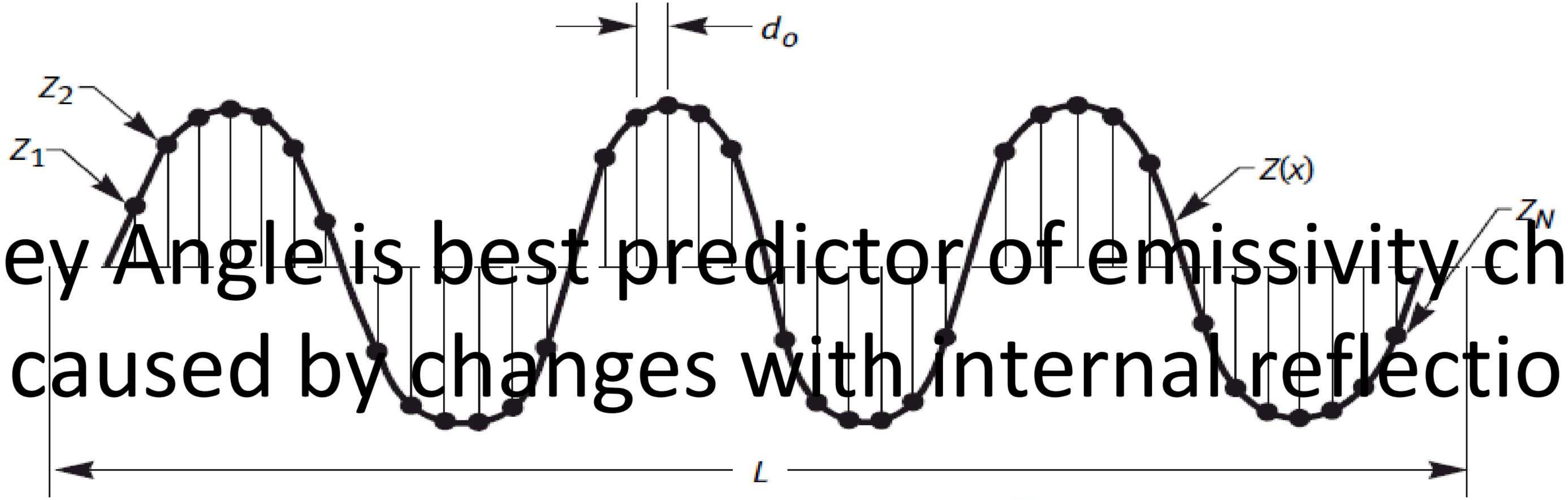
- 2 Skewed Triangles + variable height isosceles triangle
- Periodic Boundaries
- Variables
  - Height: 0-25 microns
  - X position of skewed triangle peaks: 0-20 microns



Skewed Triangle Results



Simulation Conclusions



Valley Angle is best predictor of emissivity changes caused by changes with internal reflections

$$R_a = \frac{1}{L}\int_0^L |Z(x)|\,dx$$

$$R_q = \sqrt{\frac{1}{L}\int_0^L Z(x)^2\,dx}$$

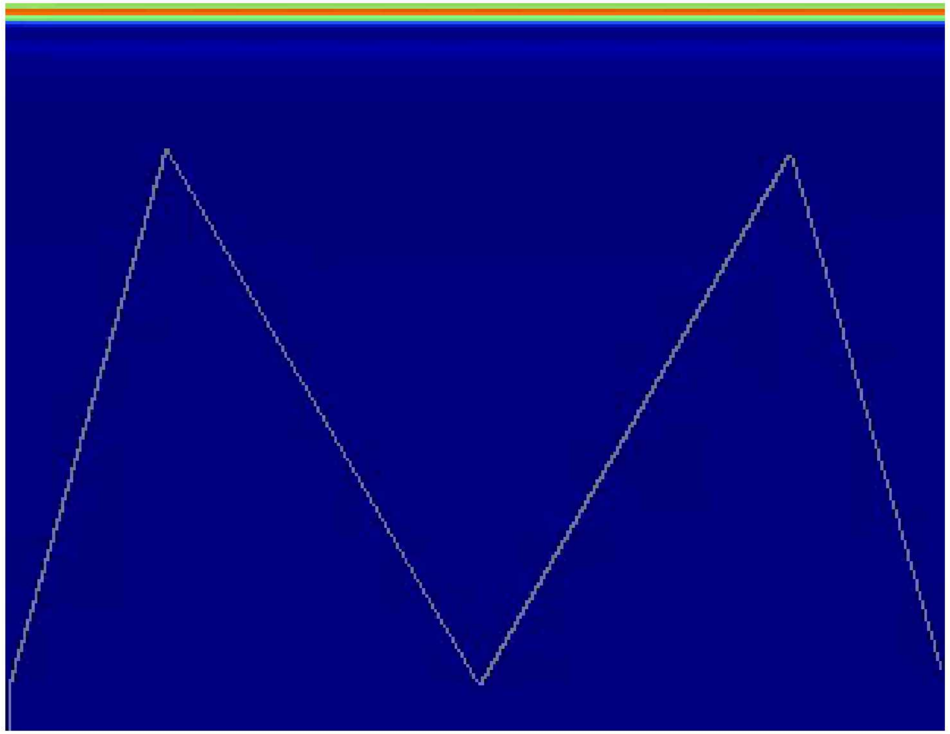
$$R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ}{dx}\right)^2 dx}$$

$$R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|}\,dx$$

Sourced from: ASMBE B46.1

Phenomenological Explanation

- Internal reflections increase as angle of valley decreases
- Mendenhall Wedge Effect (1911) – narrow wedges formed from a strip of material that cause black body-like behavior
- "By forming a wedge one is causing incident radiation to undergo more reflections, and hence more absorption, and hence approaching more and more closely what is called a 'blackbody'"(Taylor 1987)



Sourced from: Mendenhall, "On the Emissivity Power of Wedge-Shaped Cavities and Their Use in Temperature Measurements"

Phenomenological Explanation

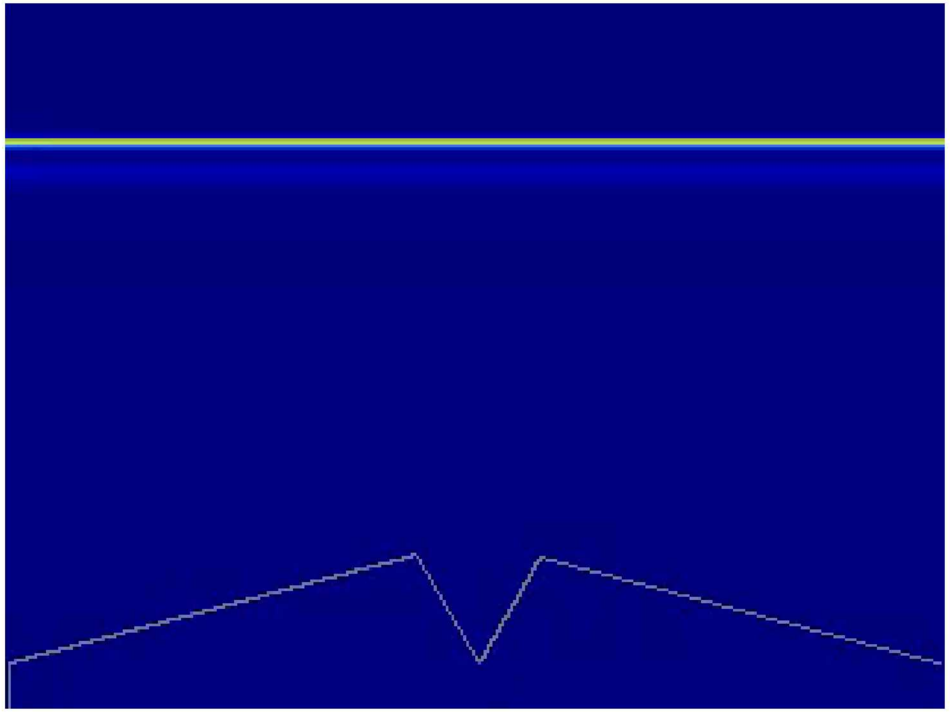
$$E \approx A = 1 - r^{\frac{180}{\theta}}$$

E = emissivity

A = Absorption

r = reflection power of the material surface

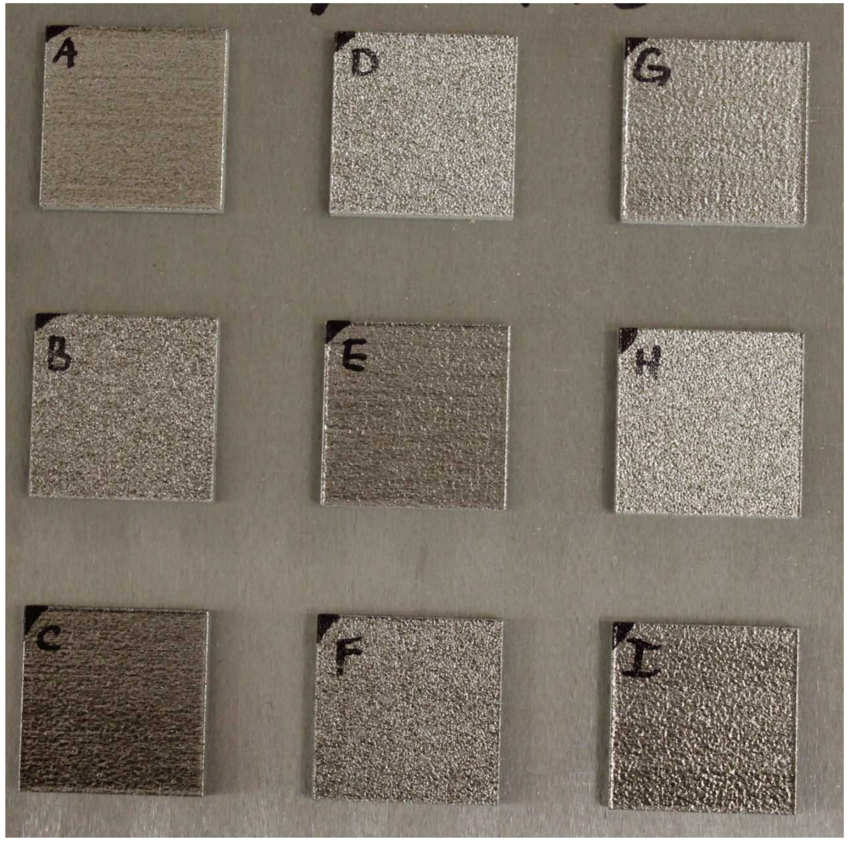
θ = internal wedge angle



Sourced from: Mendenhall, “On the Emissivity Power of Wedge-Shaped Cavities and Their Use in Temperature Measurements”

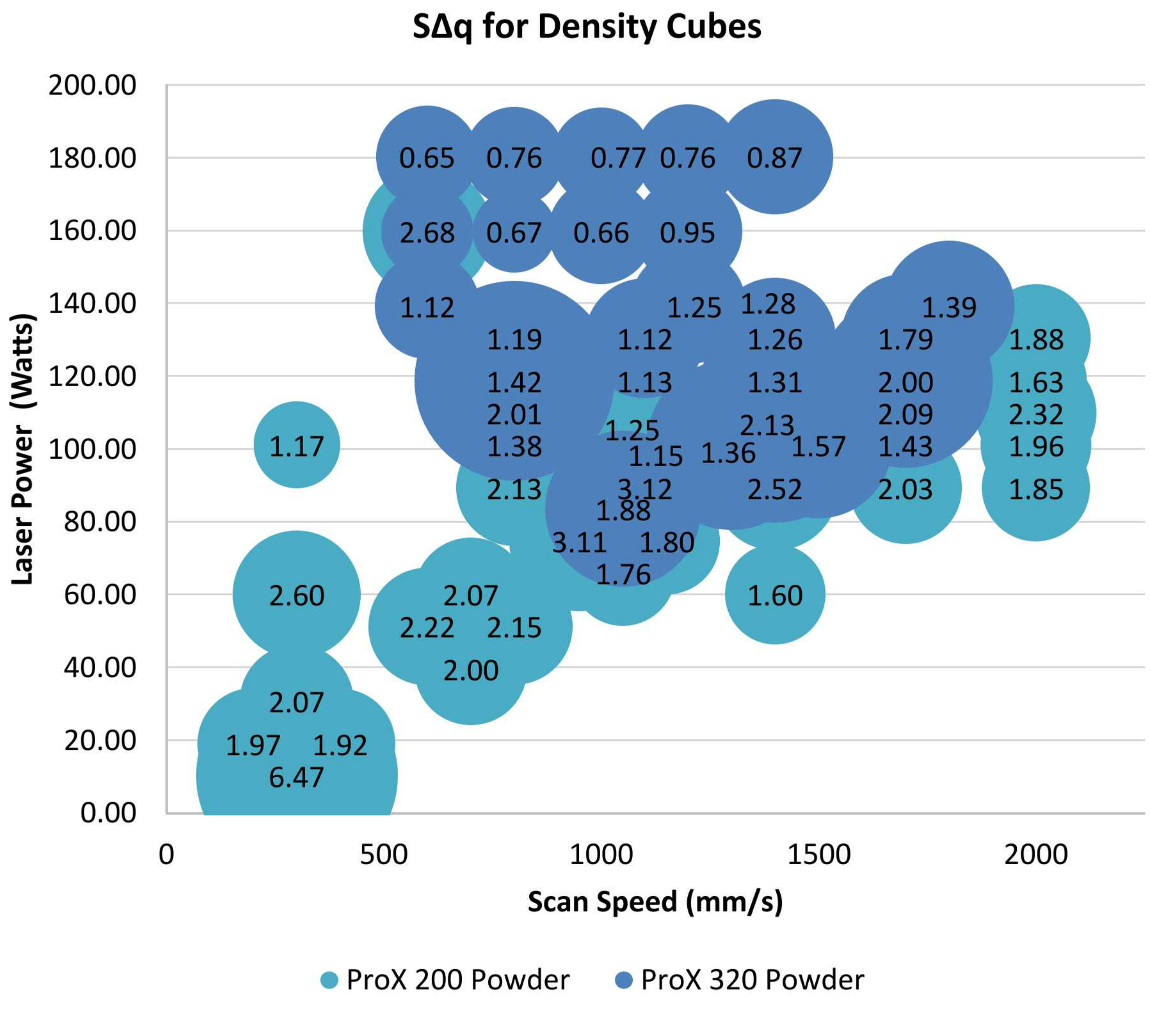
Experimental Evaluation of Surface Roughness Effects on Emissivity

- Build parameter selection
- Part fabrication
- Surface roughness measurements
- Emissivity measurements
- Correlation between emissivity and surface roughness parameters
- Oxide comparison measurements



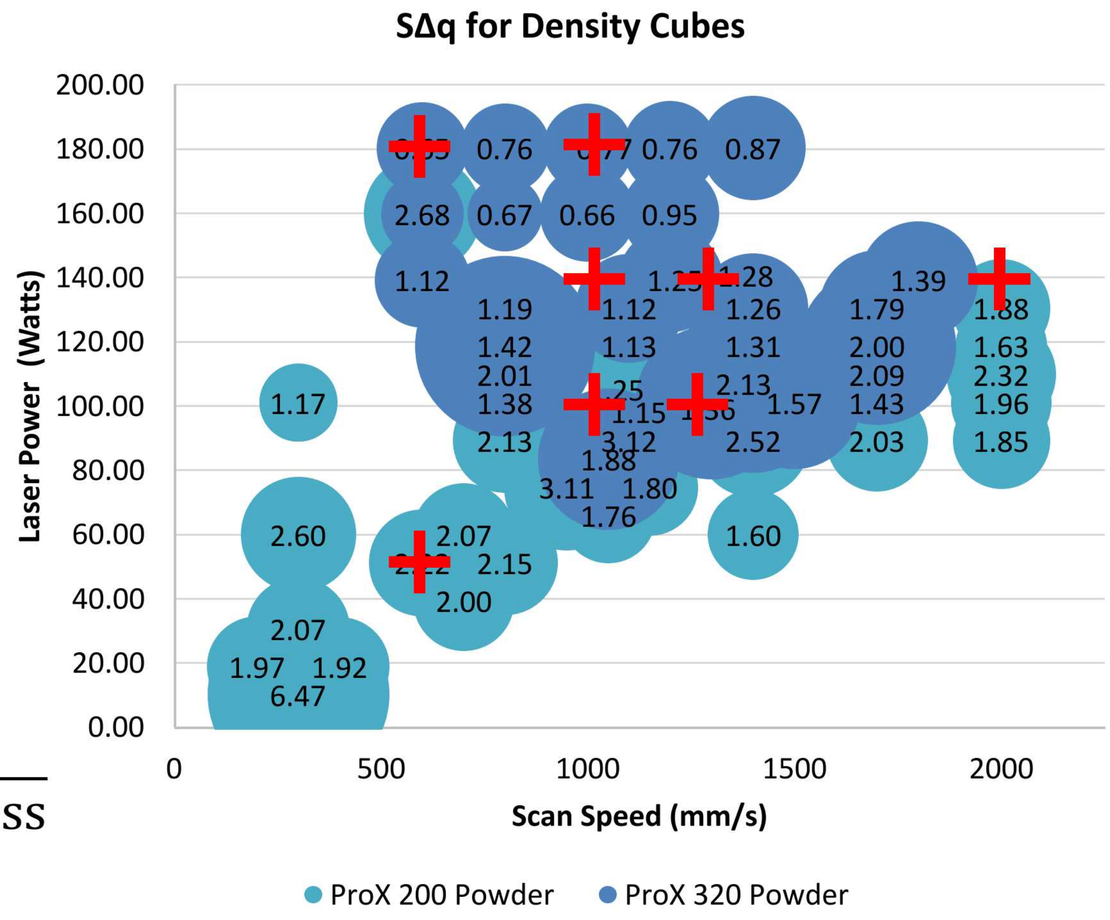
Sample Build Setting Selection

- Build parameter exploration common when bringing up an AM machine
- Variables included:
  - Laser power, scan speed, layer thickness, powder size
- Properties measured:
  - Surface roughness, density, tensile strength, ductility



Sample Build Setting Selection

- Selected parameters by looking at:
  - Surface roughness values
  - Volumetric energy density (VED) values



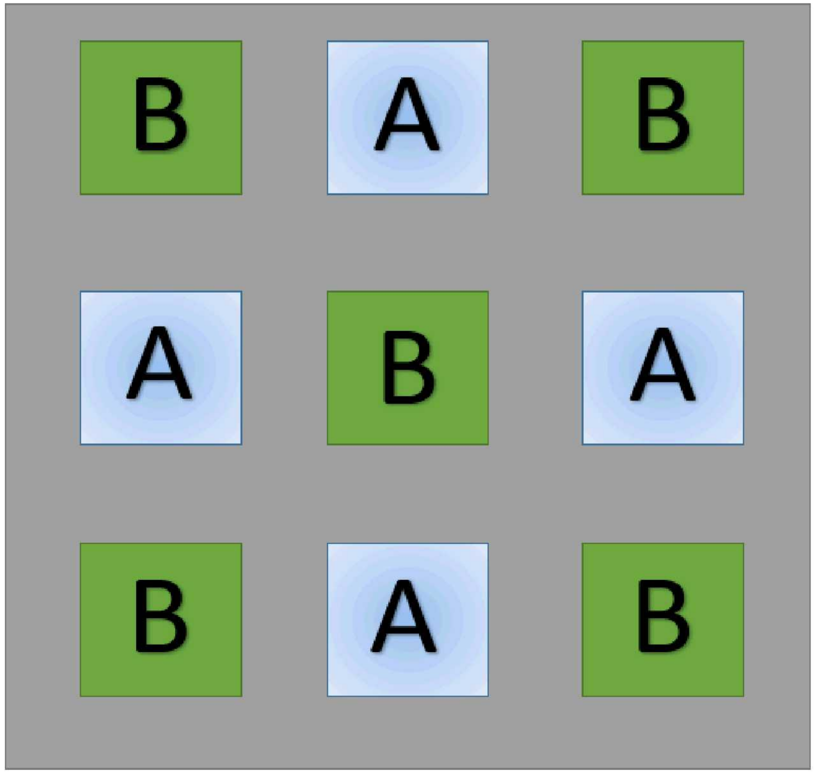
$$VED = \frac{\text{Laser Power}}{\text{Scan Speed } \times \text{Hatch Spacing } \times \text{Layer Thickness}}$$

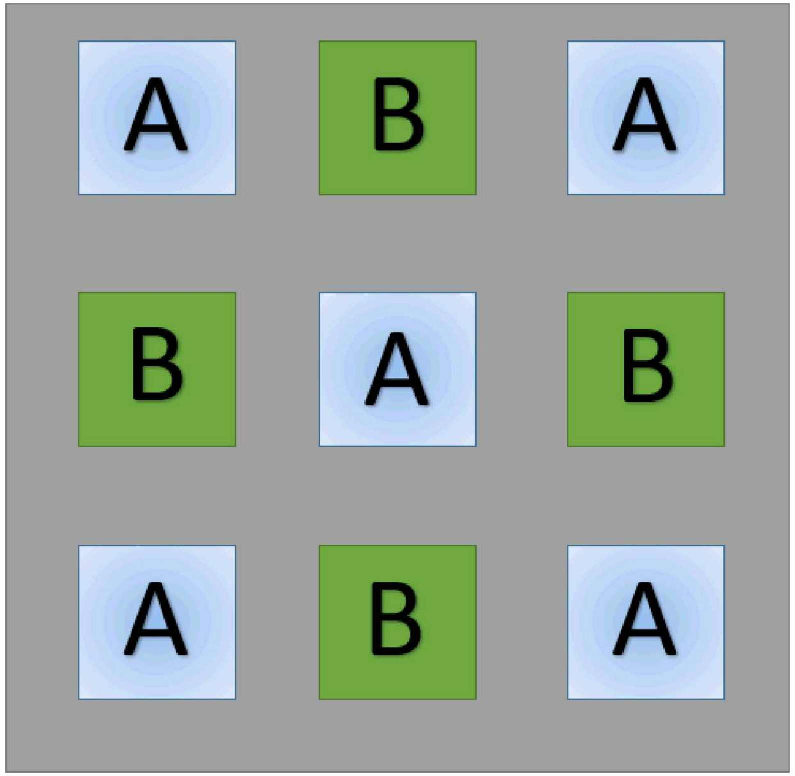
Sample Build Settings

- Geometry: 25mm square, 6mm thick
- Scan Strategy: 0/90
- Hatch Spacing: 50 microns
- Laser Spot Size: 100 microns
- Layer Thickness: 30 microns
- Powder: ProX 320 316 SS
  - Mean particle size: 25 microns

Set	Parameter	Laser Power	Scan Velocity	VED (J/mm^3)
1	A	180 W	600 mm/s	200
1	B	50 W	600 mm/s	55.56
2	A	180 W	1000 mm/s	120
2	B	100 W	1000 mm/s	66.67
3	A	100 W	1400 mm/s	47.62
3	B	100 W	2000 mm/s	33.33
4	A	140 W	1000 mm/s	93.33
4	B	140 W	1400 mm/s	66.67

Build Layouts

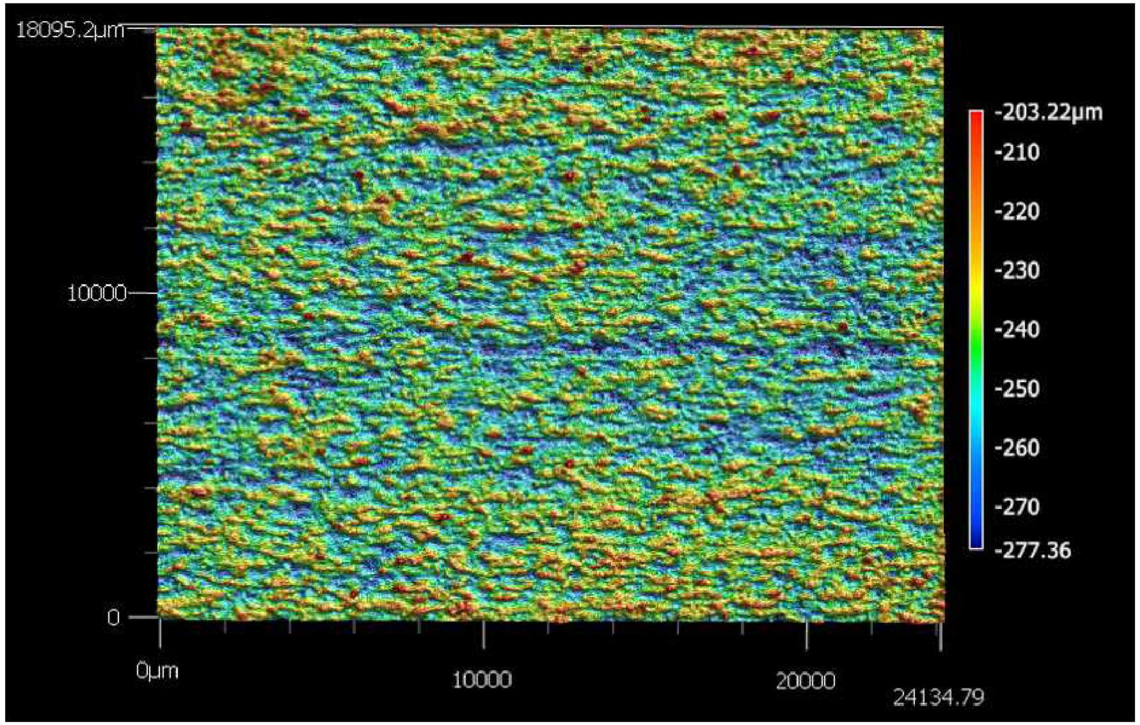




Completed Builds – 72 parts

Potential Surface Roughness Measurement Techniques

- X-ray Coherence Tomography (XCT)
  - Insufficient resolution for entire area of part
  - Surface detection issues (grayscale images)
- White light interferometry
  - Surface too rough
- Stylus-based contact profilometry
  - Possible aliasing
  - Possible damage to equipment
- Fringe pattern projection microscopy
  - Large areas of measurement
  - High resolution
  - Non-contact



Keyence VR3100 Microscope

- Uses light triangulation to measure height of samples
- Light bands are illuminated onto surface and CMOS sensor looks at light distortion to calculate height map
- Can measure height differences up to +/-5 mm
- Can measure up to 3 cm square with no distortion due to specialized lenses
- Raw surfaces output in excel spreadsheet for further analysis

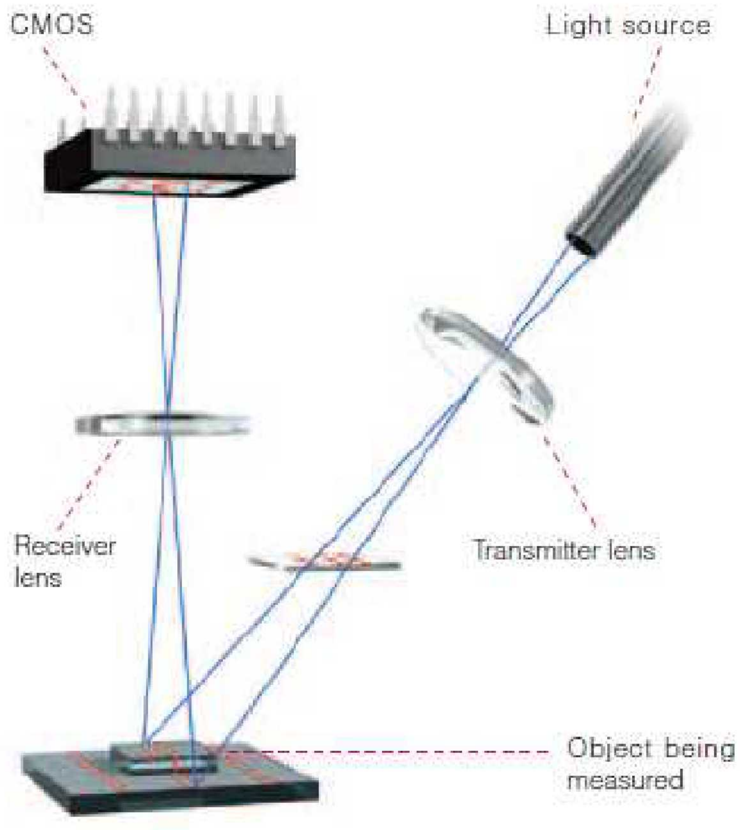
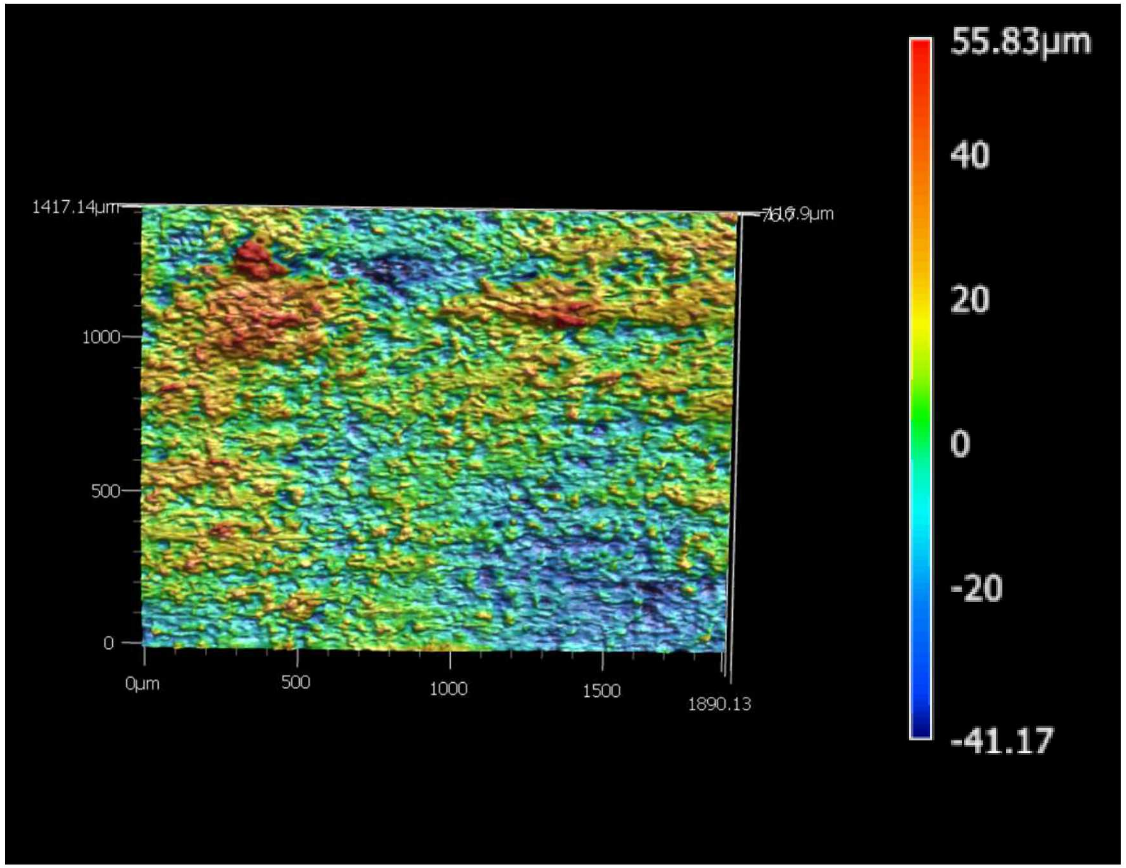


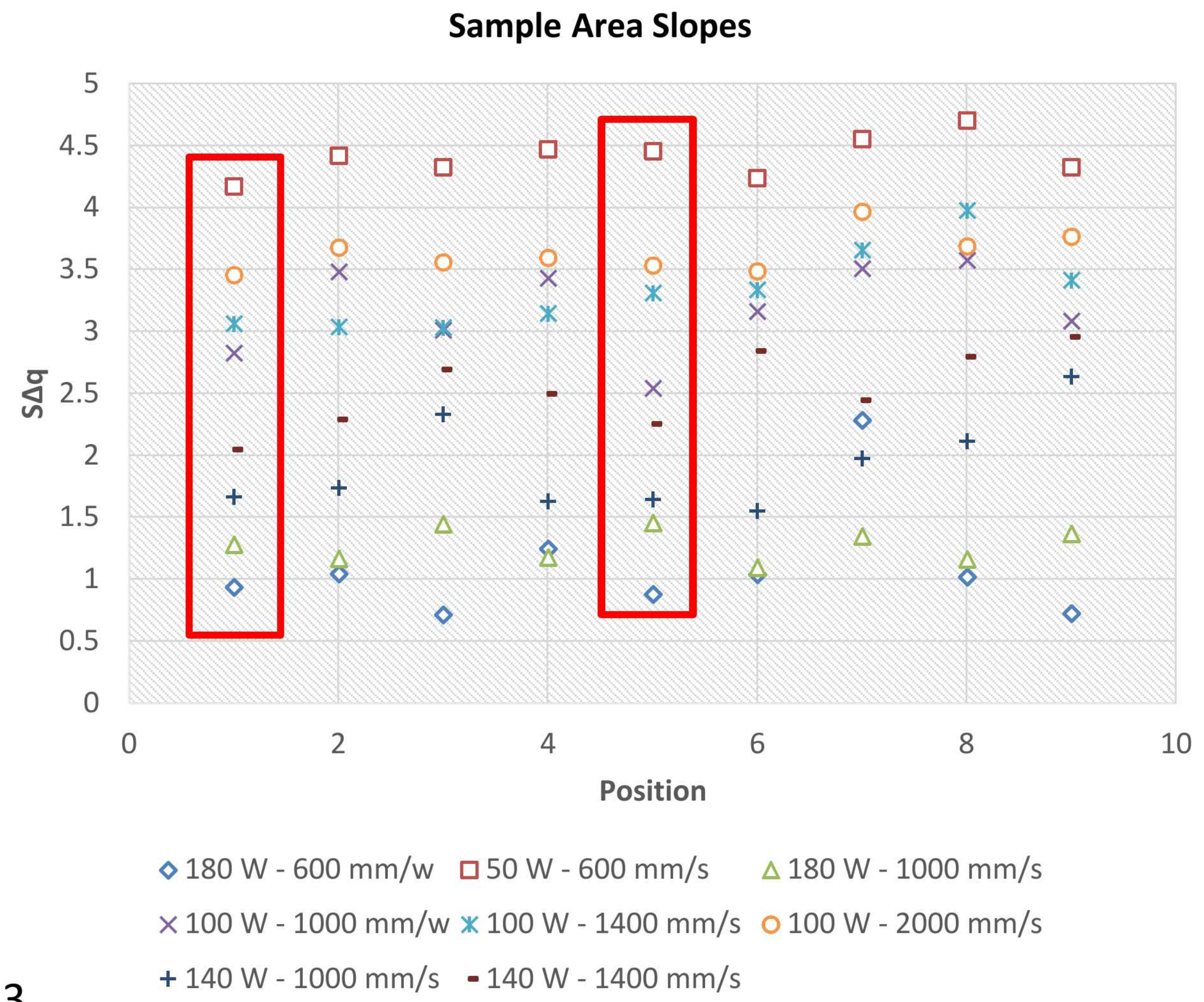
Image from: Keyence One-shot Measuring Macroscope VR-3000 Series

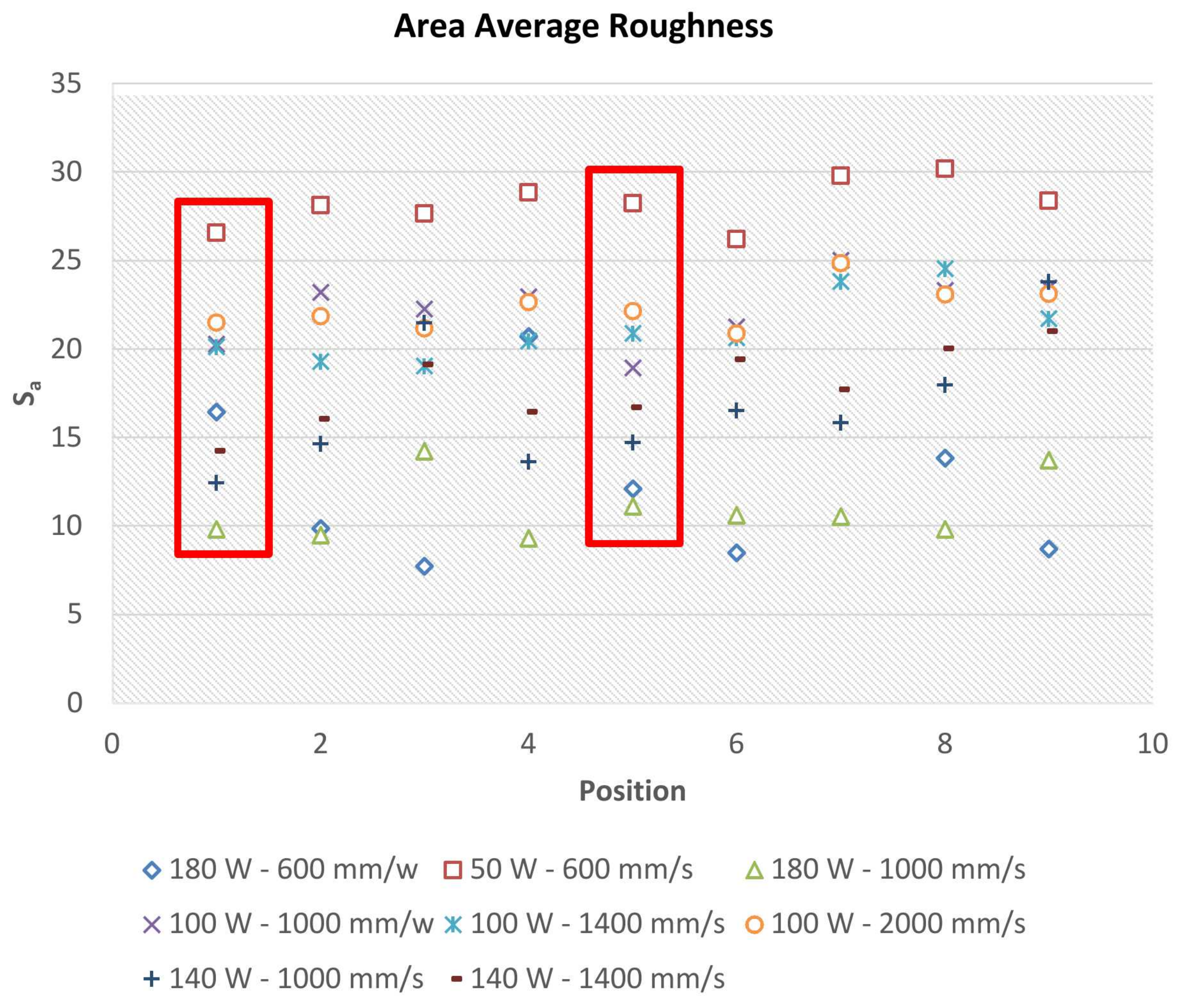
Surface Roughness Analysis

- Custom MATLAB program
- Input was raw height maps
- No filtering except plane removal
  - Least squares plane
- Multiple zooms/resolutions used
- Standard and custom SR parameters calculated



Surface Roughness Results





Emissivity Measurements

- Hemispherical Directional Reflectometer (HDR)
  - Directional reflectance is measured at 5-10 degree increments
  - Radiation reflected from sample is directed by a mirror that directs radiation to the coupled FTIR
- Wavelength Range: 2.5-24 microns
- Time intensive due to multiple measurements taken at each angle

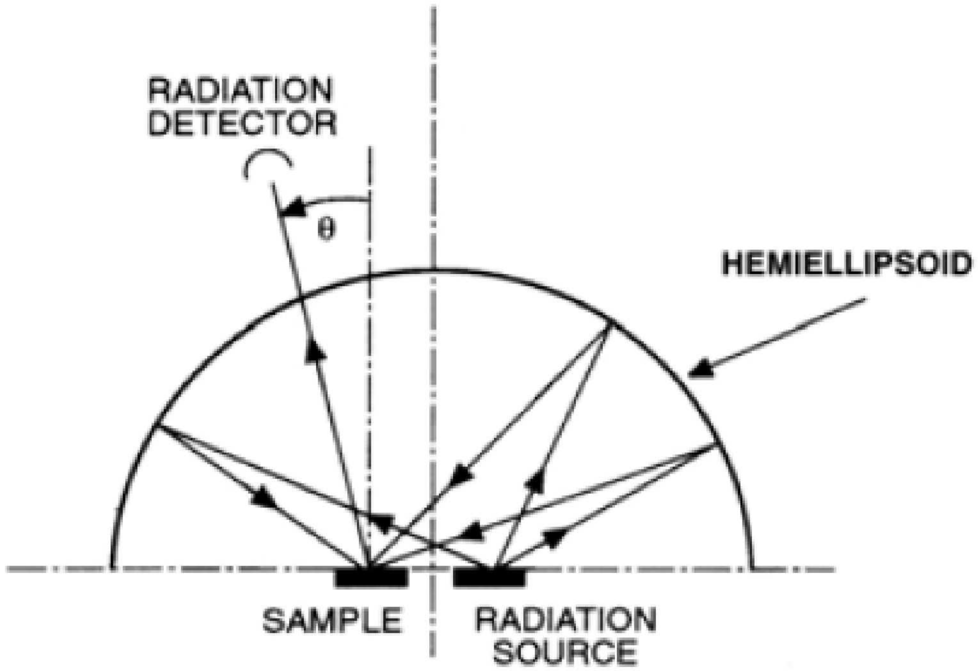


Image from: Surface Optics Corporation, SOC-100 HDR

Emissivity Measurements

- Fourier Transform Infrared Spectroscopy
  - Using interference of able to produce multiple spectra from broad band light source
  - Analyzes the various reflected spectra off the sample to determine reflection at specific wavelengths

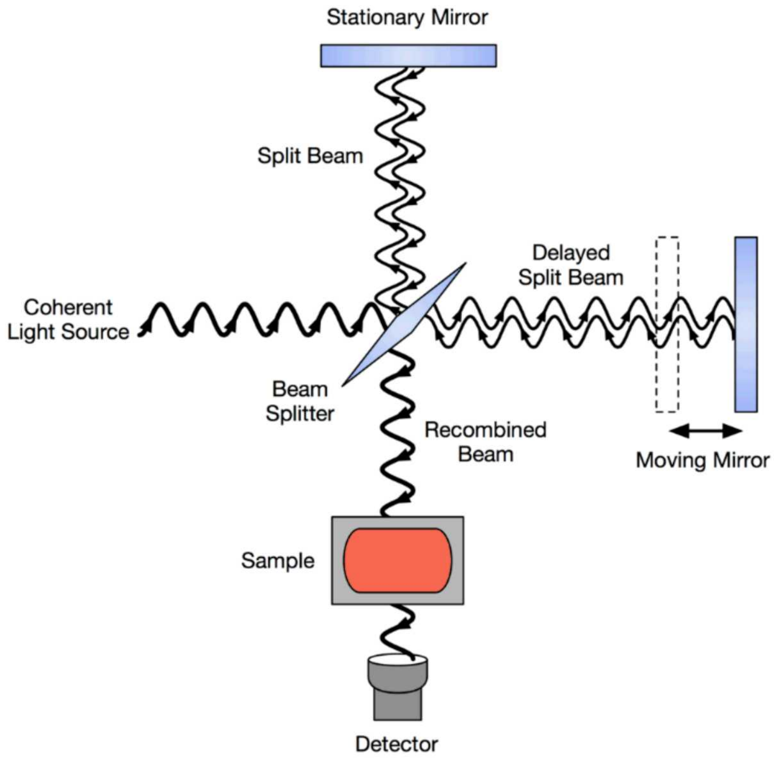
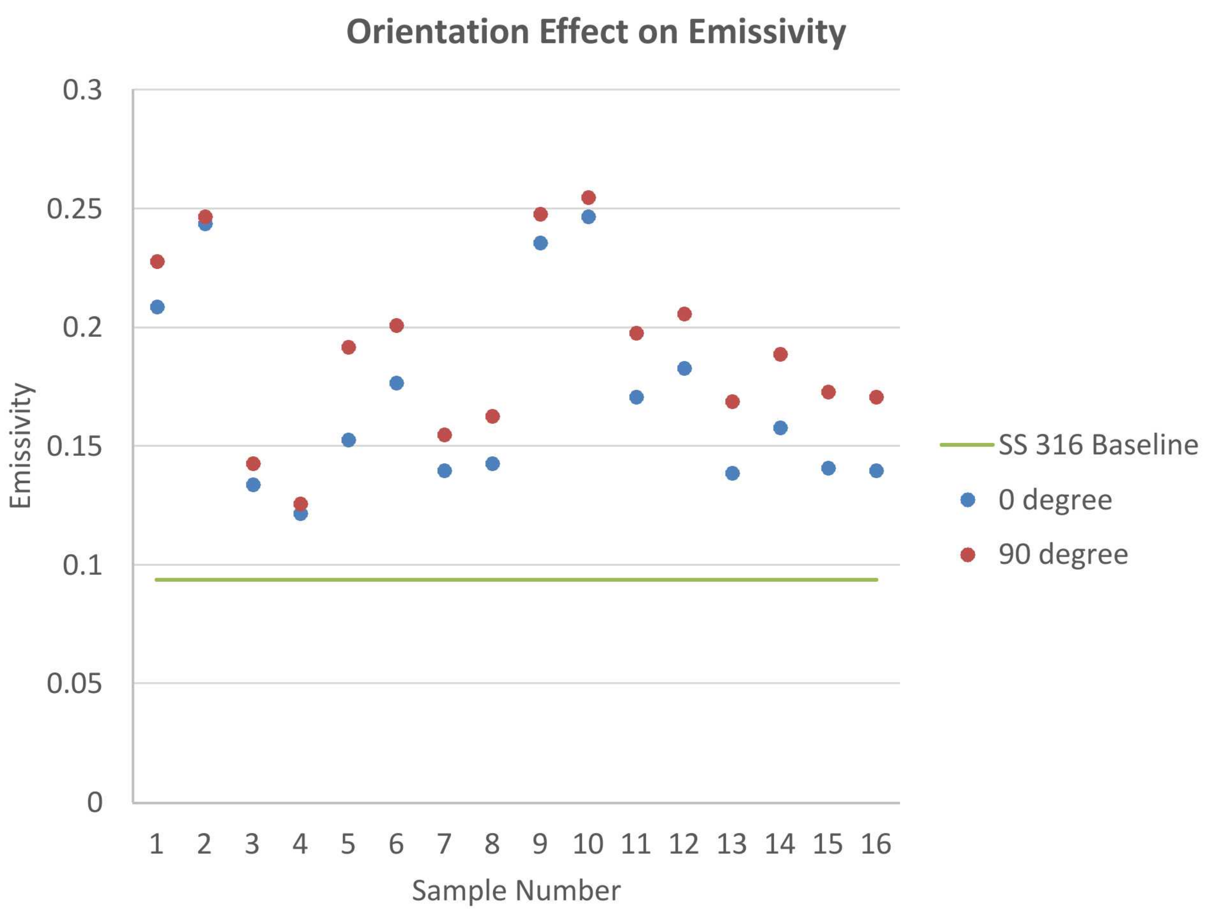
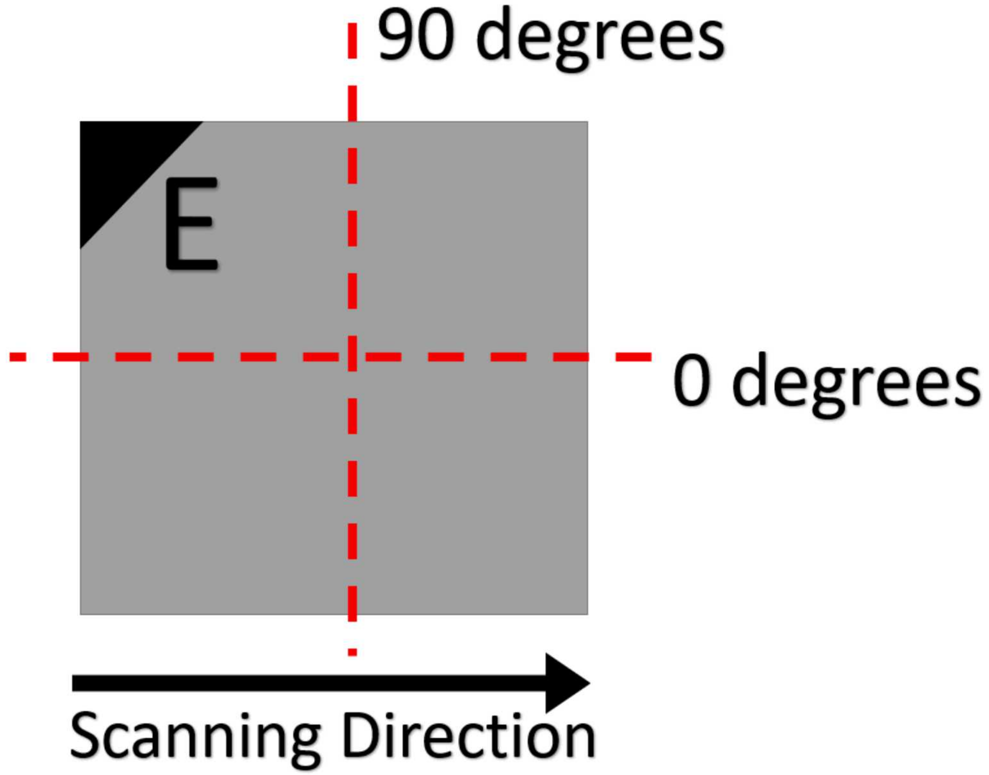


Image from: https://en.wikipedia.org/wiki/Fourier-transform_infrared_spectroscopy

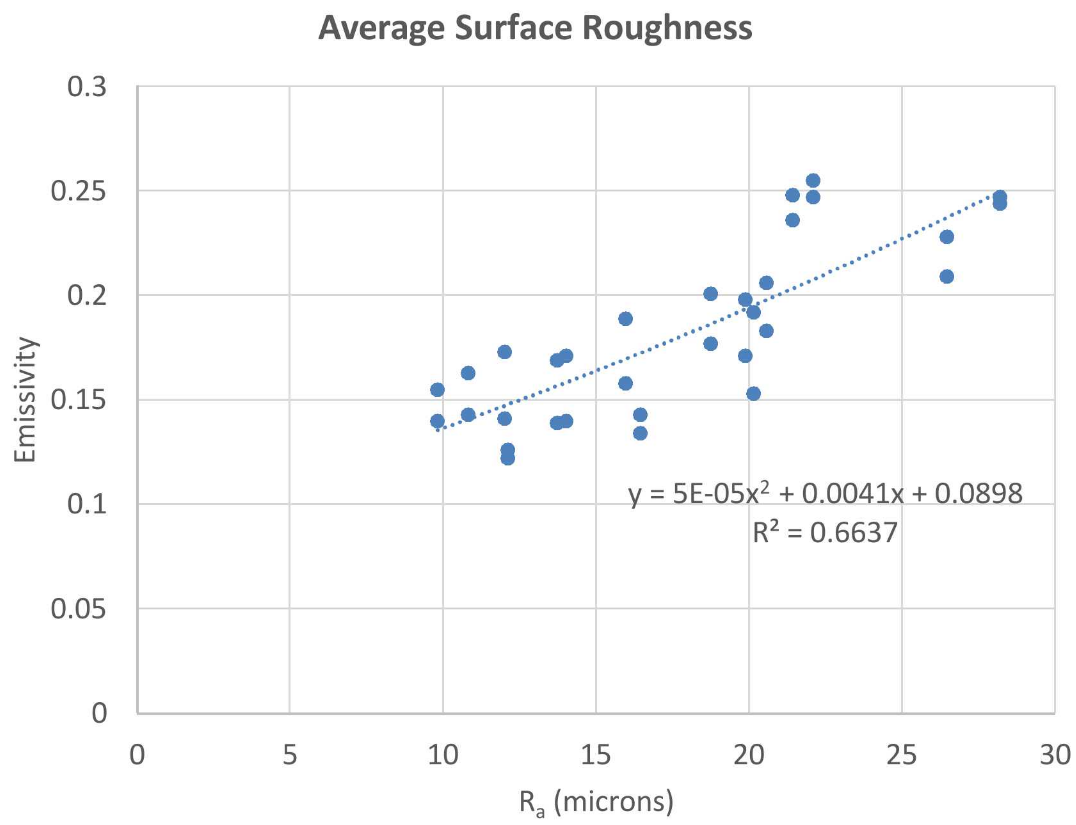
Emissivity Measurements





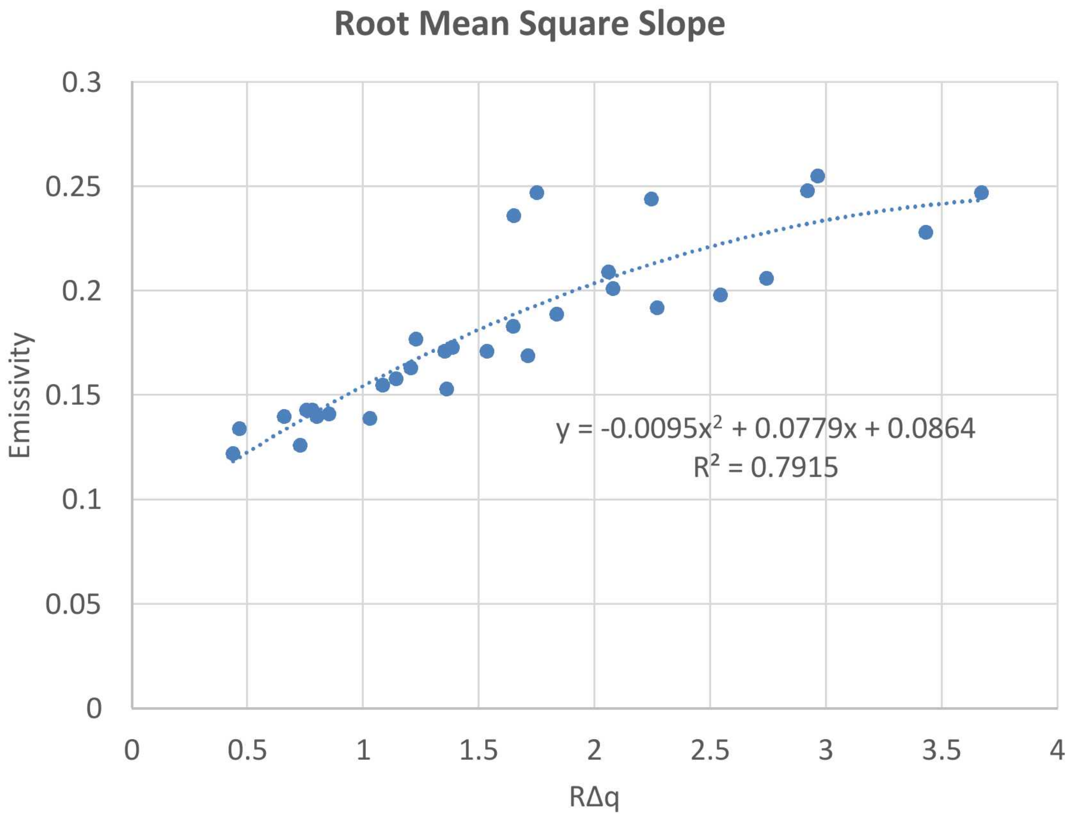
R_a Relationship with Emissivity

- Poor descriptor of emissivity changes
- R^2 (correlation coefficient)
  - Value represents how closely the predictive best fit line fits the emissivity data based on R_a values



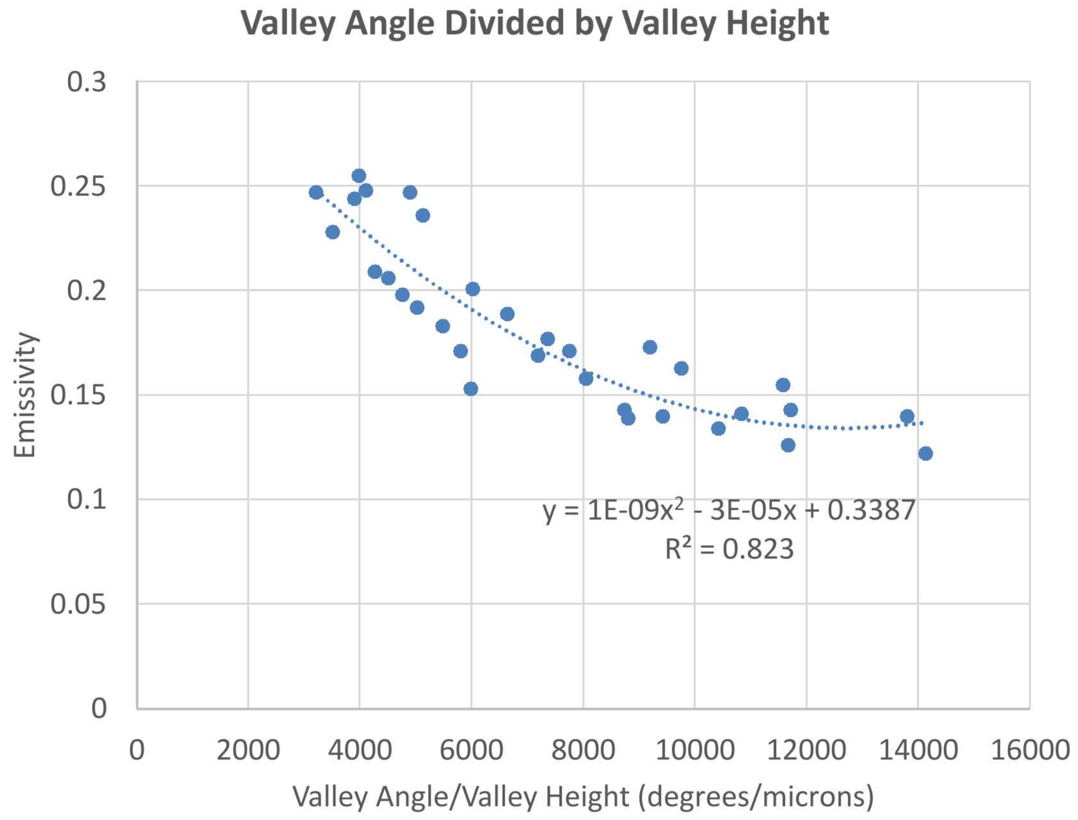
RΔq Relationship with Emissivity

- RΔq was a better indicator of emissivity trends than R_a
- R^2 value improves significantly



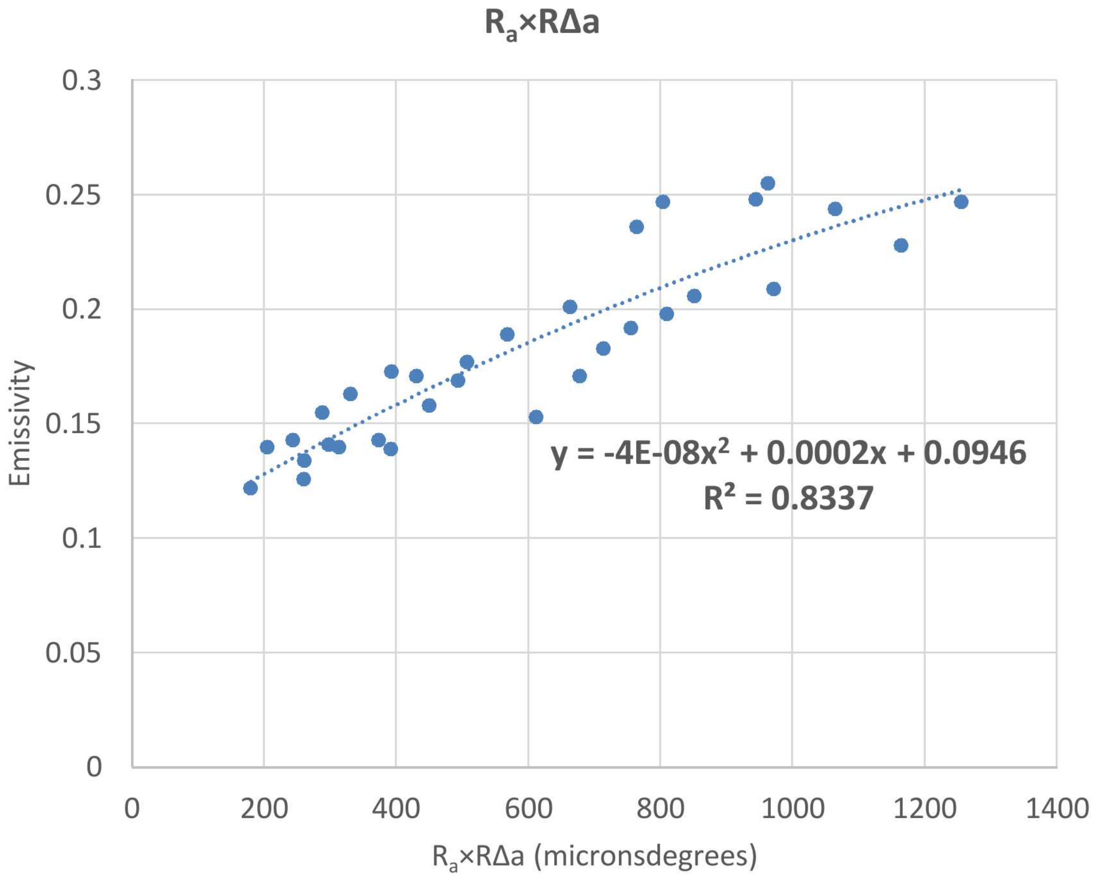
Best New Parameter Correlation

- Valley geometry dictates amount of internal reflections
- New parameters are not preferred however
- Had highest R^2 value for all new surface parameters

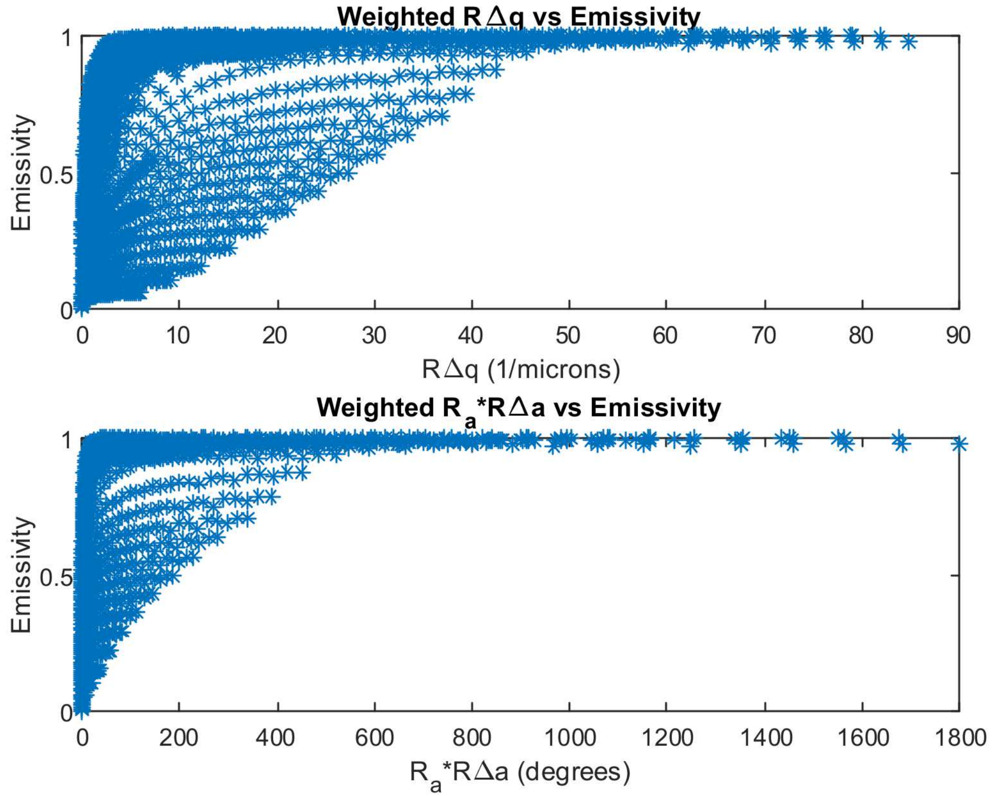


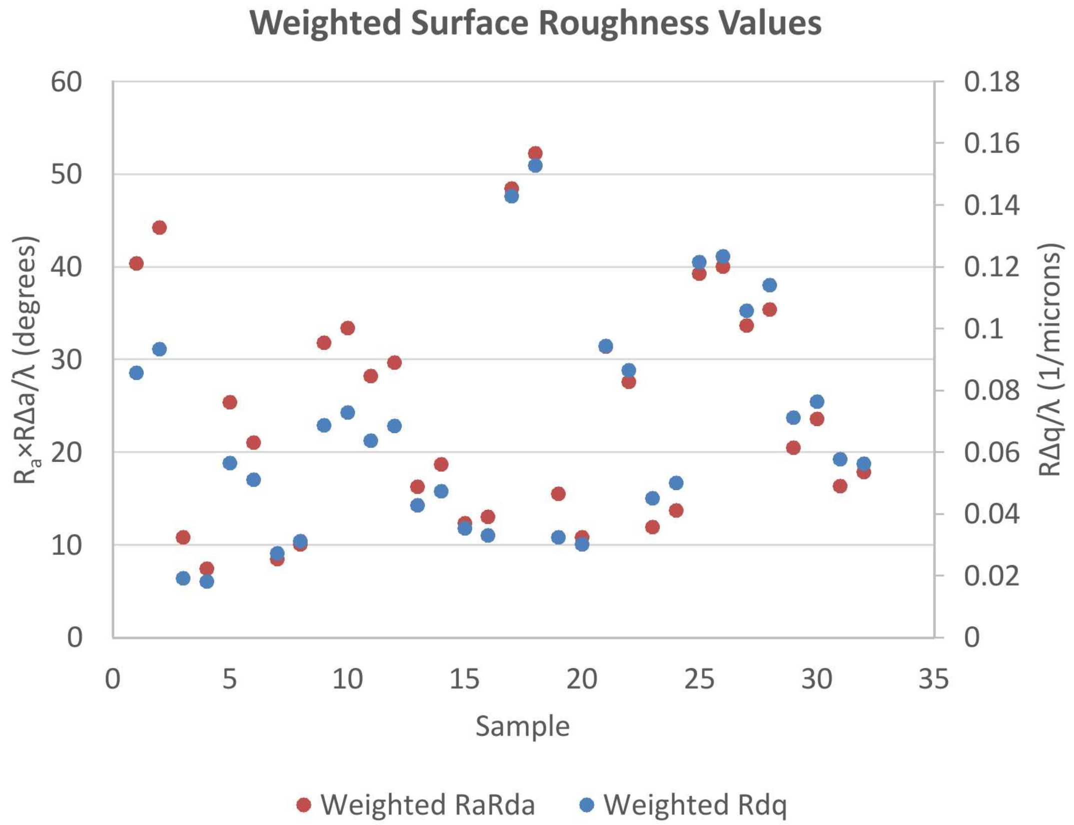
Best Existing Parameters Correlation

- Product of arithmetic mean height and arithmetic tilt angle gave best correlation
- Best fit line equation will be used to estimate emissivity value based on roughness measurements in future tasks

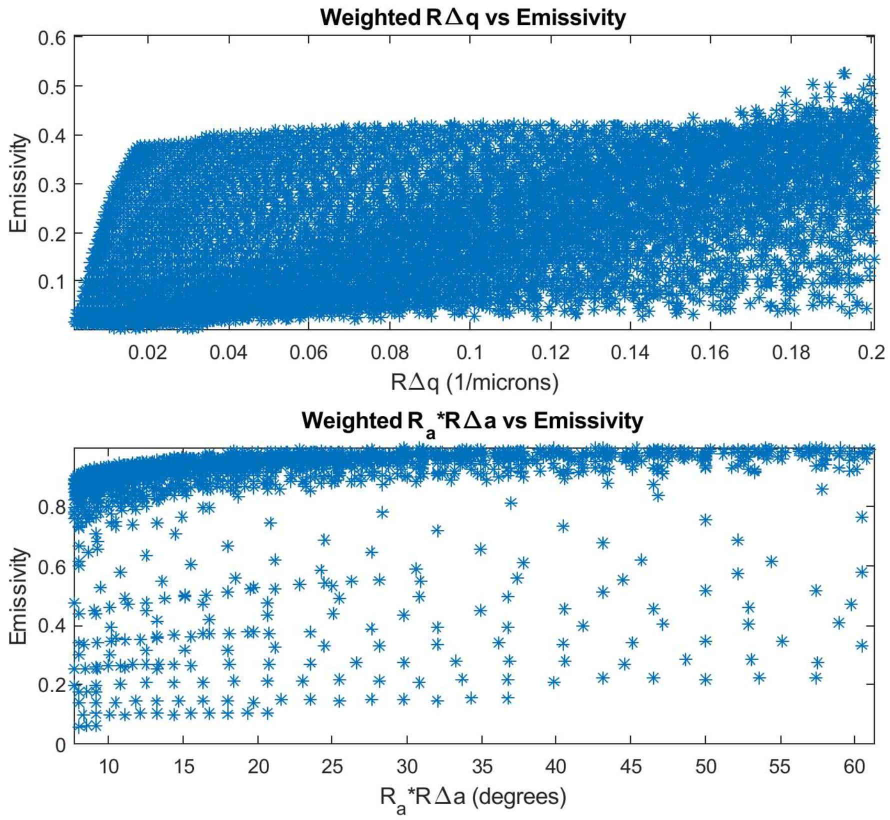


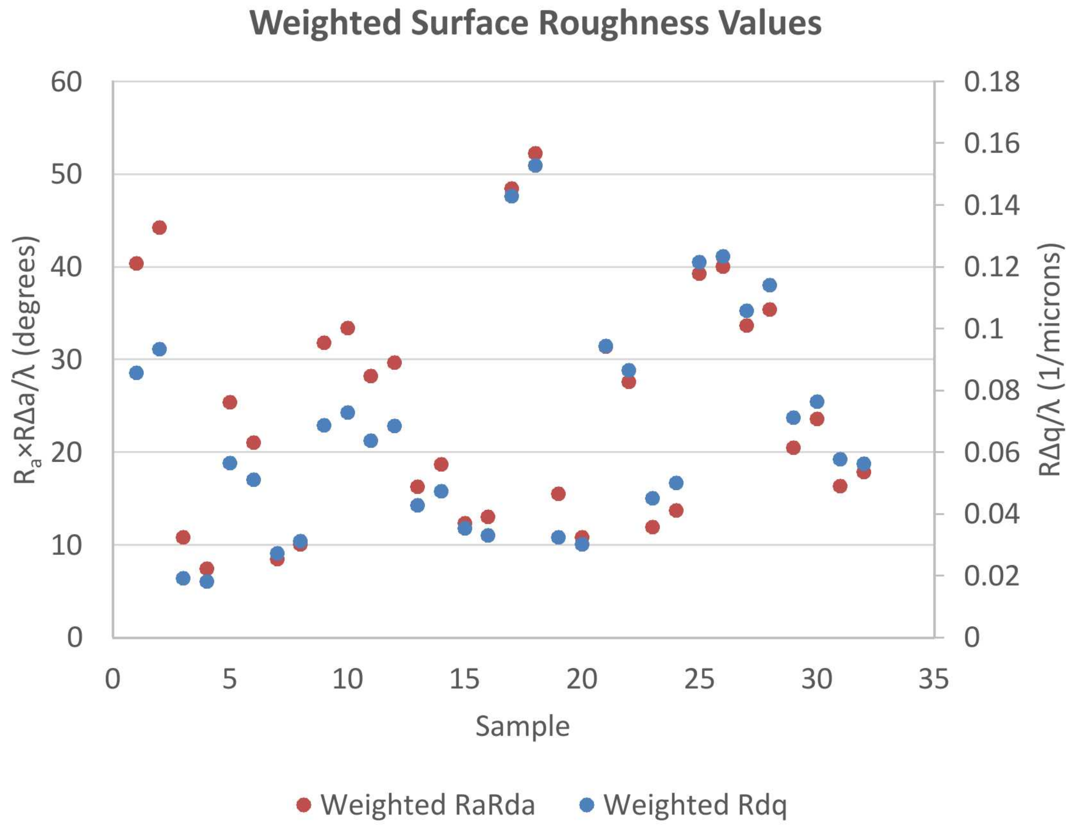
Non-dimensional SR parameters – Weighted by Wavelength



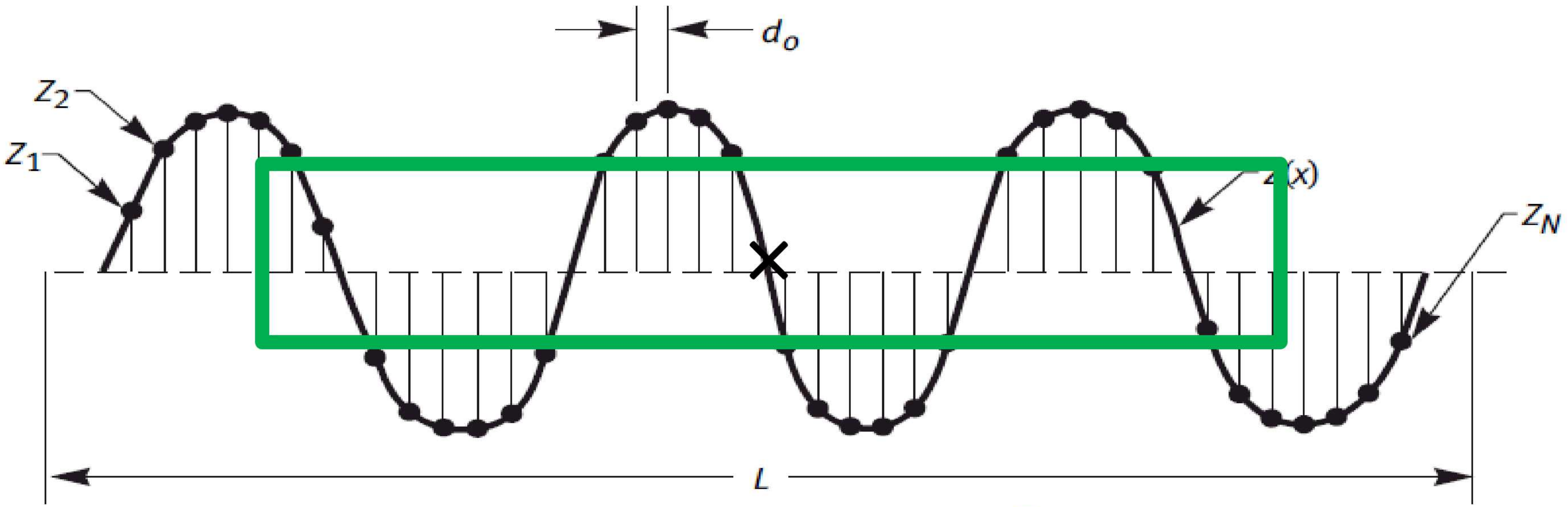


Difference between RΔq and R_a×RΔa





Experimental Conclusions



$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx \qquad R_q = \sqrt{\frac{1}{L}\int_0^L Z(x)^2 dx} \qquad R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ}{dx}\right)^2 dx} \qquad R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|} dx$$

Sourced from: ASMBE B46.1

Experimental Conclusions

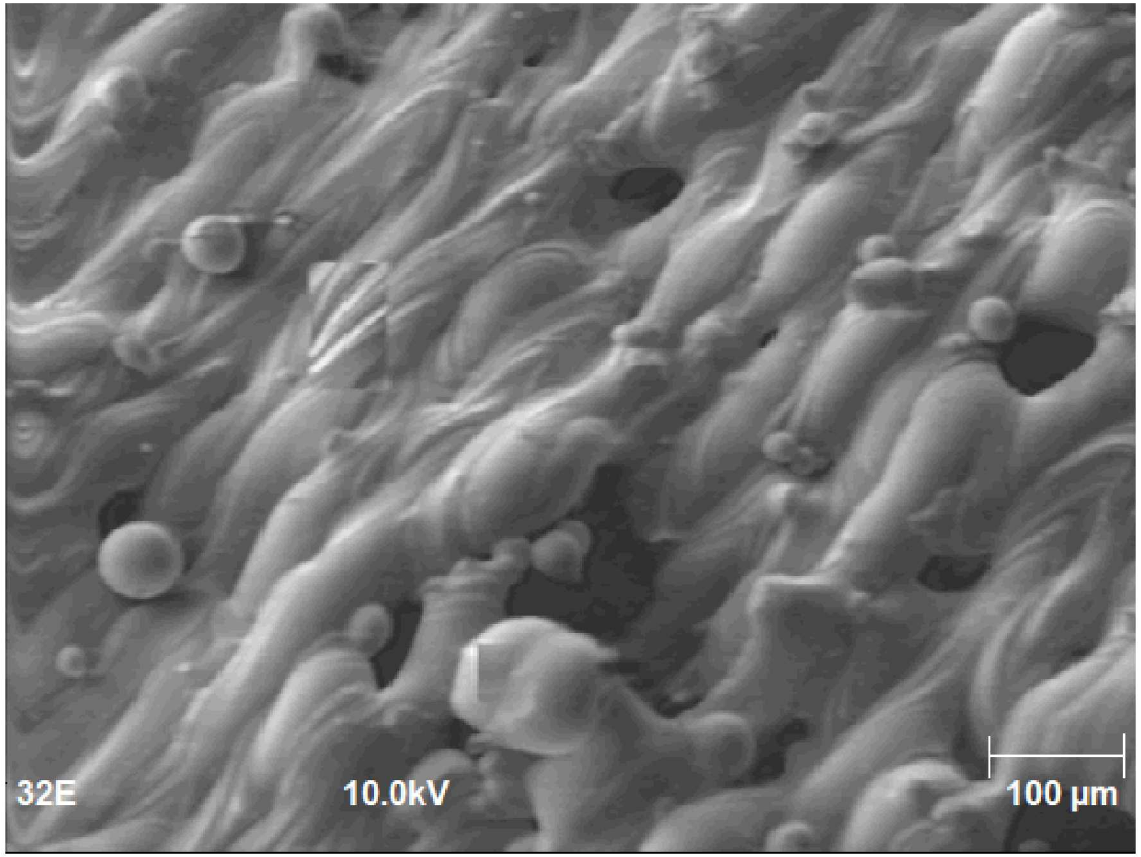
$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx \times R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|}dx$$

Product of Ra and RΔa had the best correlation with emissivity trends

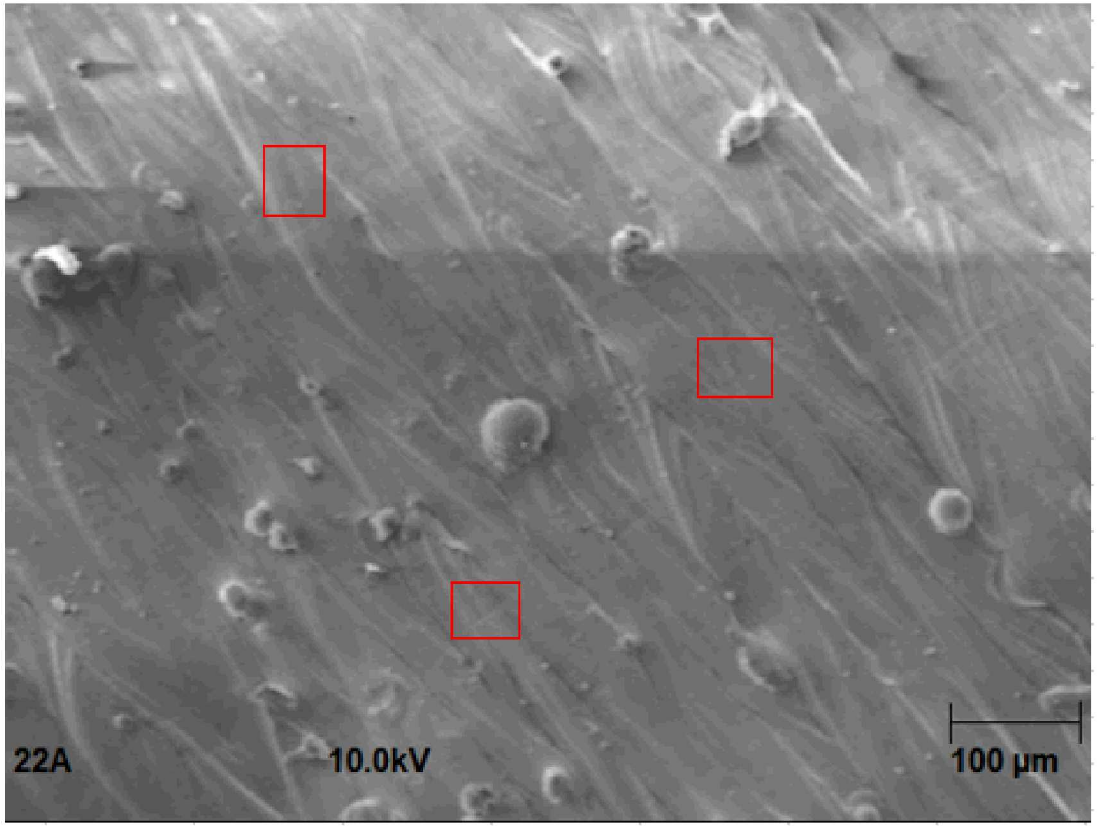
Sourced from: ASMBE B46.1

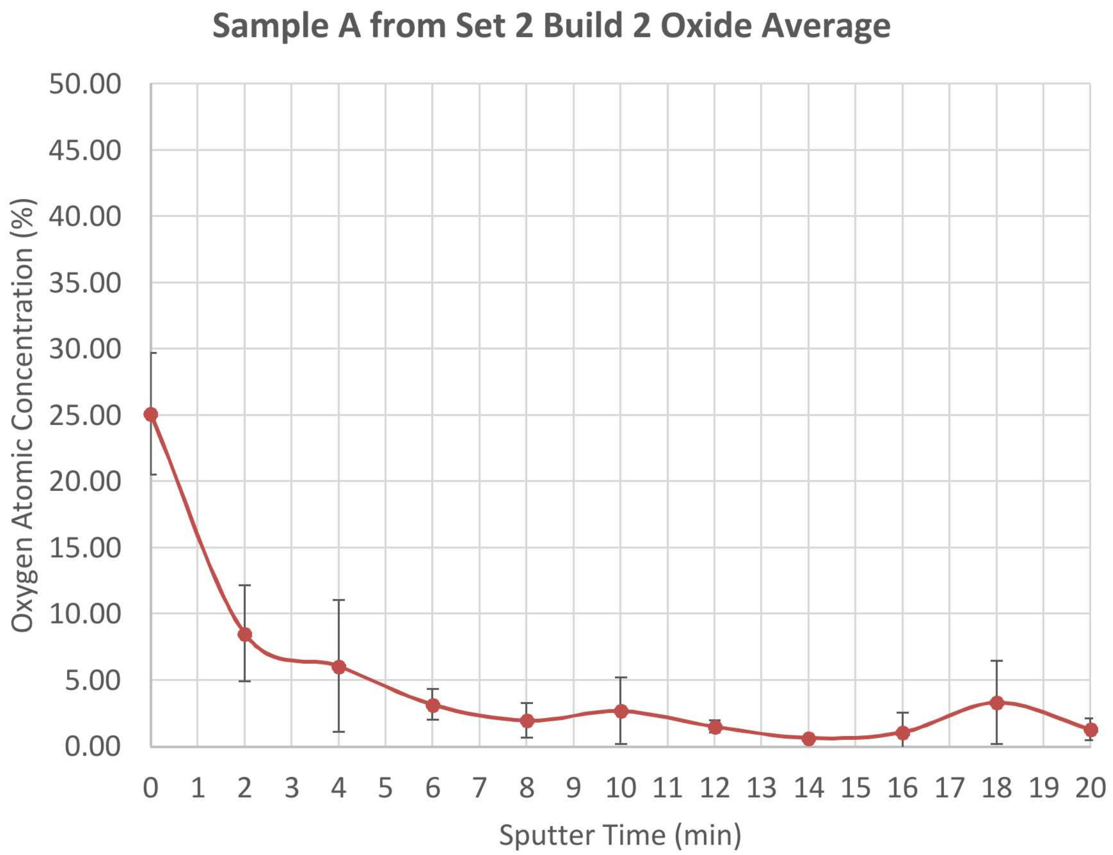
Oxide Comparison Measurement

- To ensure oxide layer on surface did not contribute significantly to emissivity trends
- Auger Electron Spectroscopy (AES) used
  - Mills surface at micro-level with Argon ion source
  - Composition of material is measured from electron energy
  - Observe composition levels to determine thickness of oxide layer



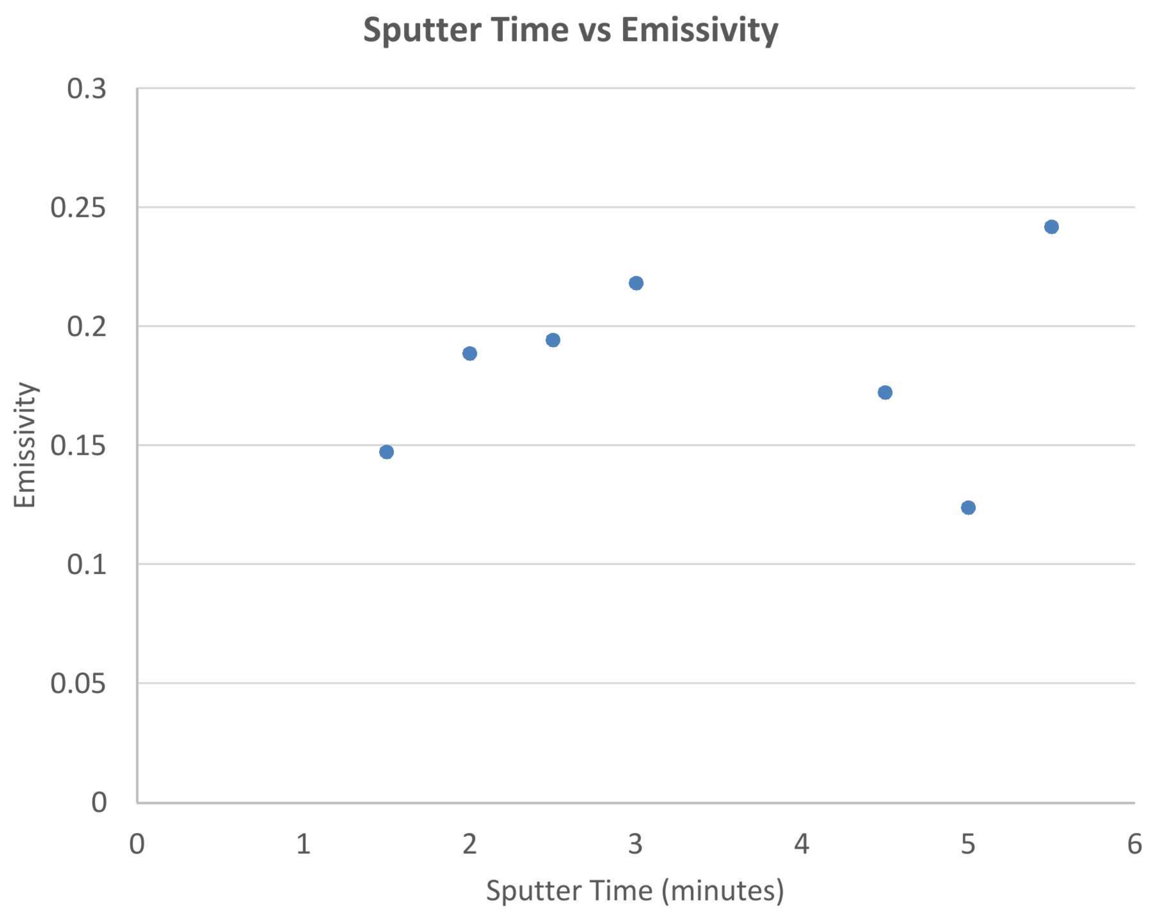
Oxide Layer Measurements - AES





Oxide Layer Measurement Comparison

- Changes in oxide layers are on the same magnitude
- Layer thickness differences insufficient for accounting for emissivity changes between samples



Task 1 Conclusions

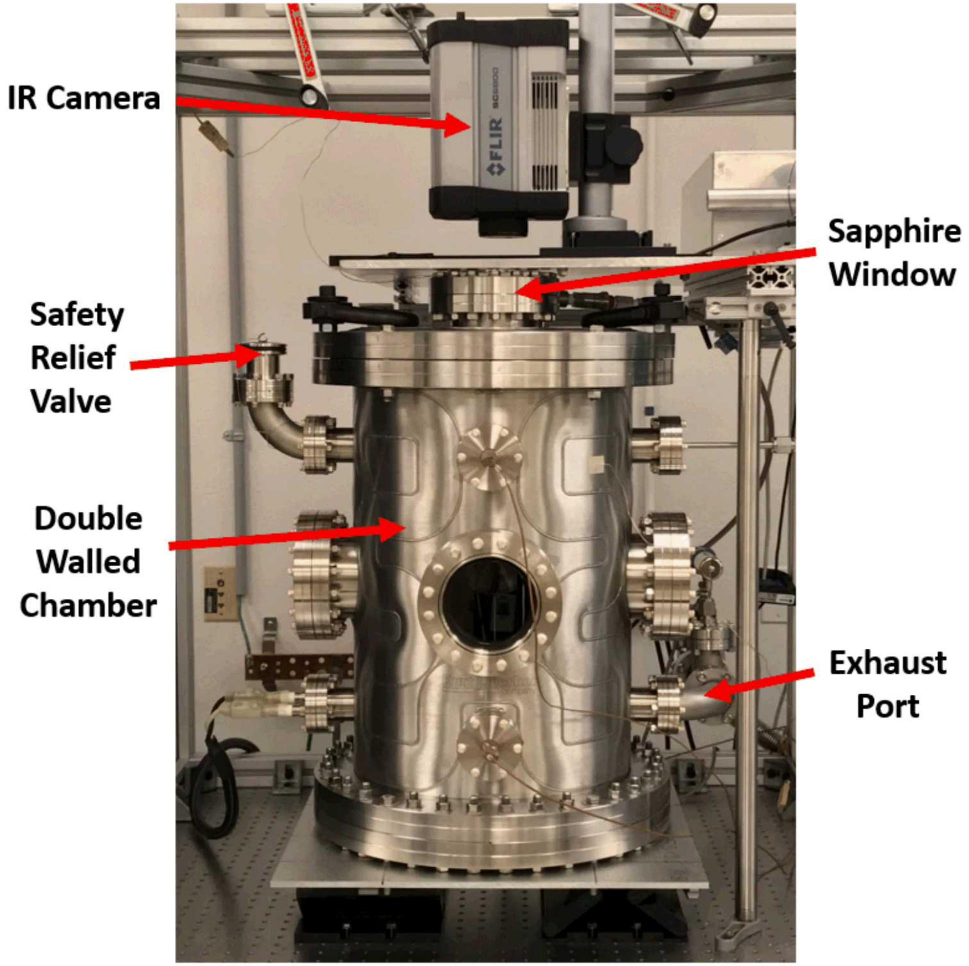
- Internal reflections are phenomena that is affecting emissivity when in the geometric optical region
- Valley angle was best indicator of emissivity changes in simulation results
- $R_a \times R\Delta a$ had the best correlation with emissivity in experimental tests

Task 2: Exploration of View Angle Sensitivity of Emissivity

- Purpose is to observe effects of view angle on emissivity for a range of sample roughness
- Angles will be 0, 30, and 45 degrees from normal (majority of literature had cameras that were 25-45 degrees from normal)
- Measurements will be taken at a range of temperatures to see if emissivity trends vary as temperature is increased

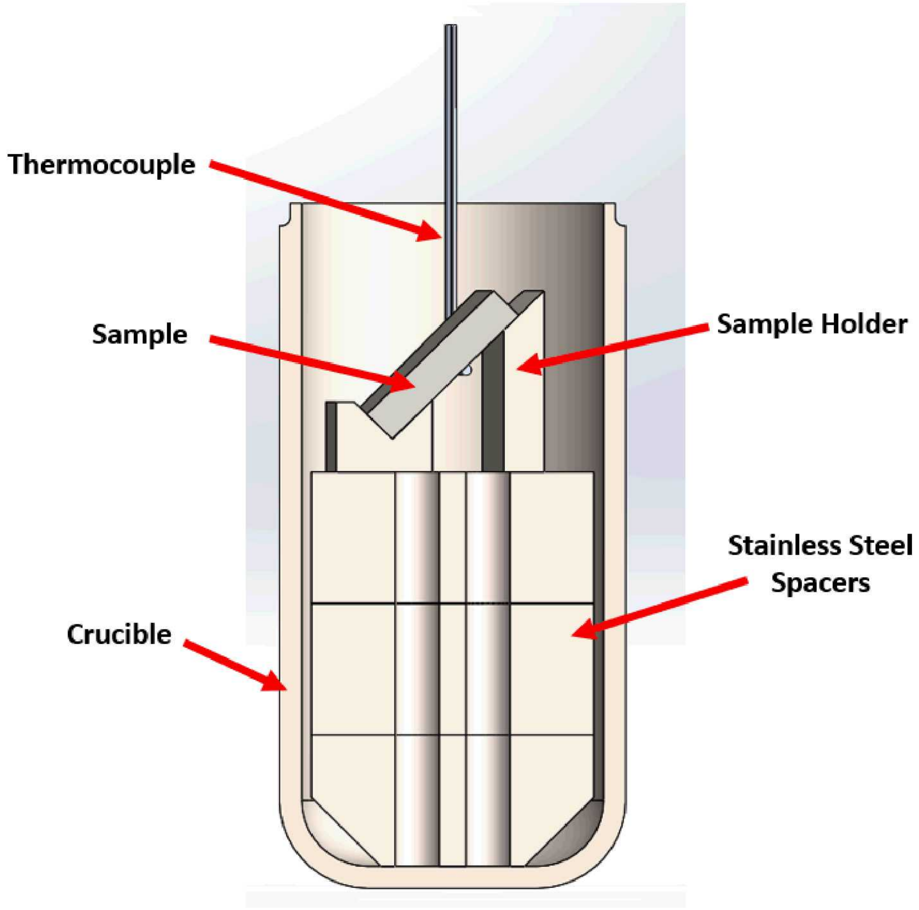
Vacuum Furnace Set Up

- Double walled chamber has cooling channels
- Argon atmosphere used to simulate in build conditions
- Sapphire viewing window limits camera options to SWIR or MWIR due to lack of transmission in the long-wave infrared range
- FLIR SC6811 MWIR camera used



Experimental Set Up

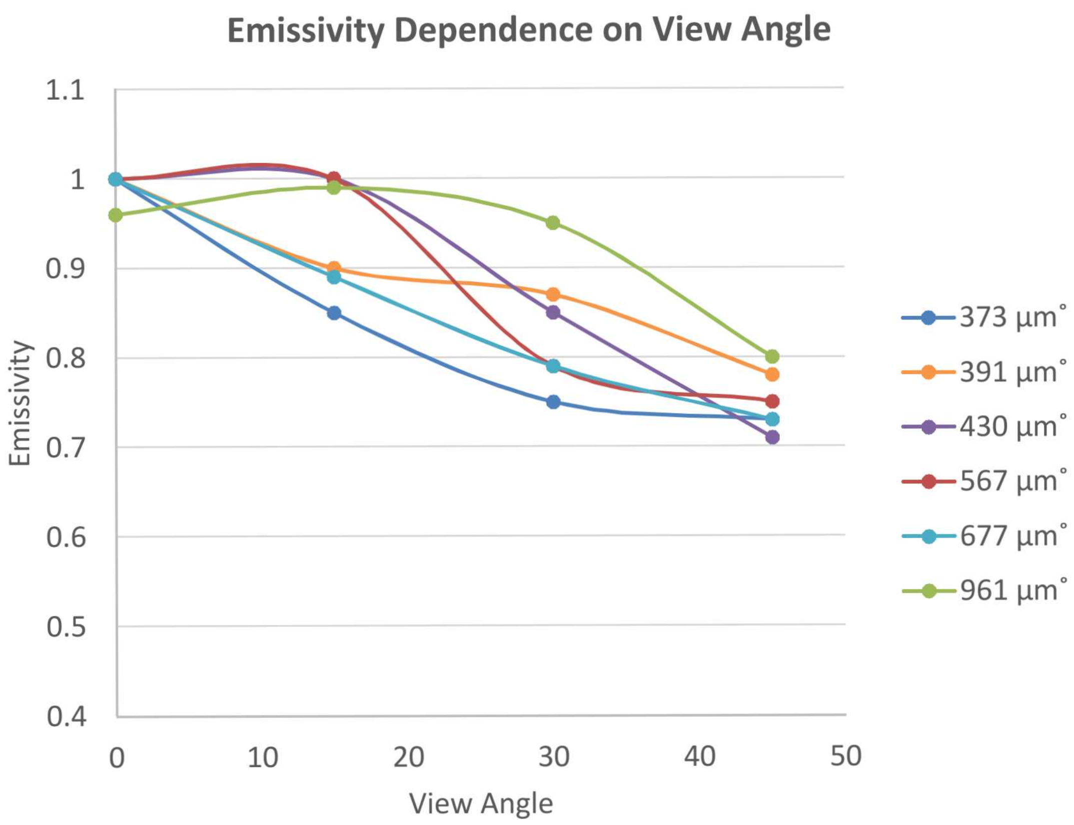
- Sample and holders contained in an aluminum oxide crucible
- Bare type K TCs welded to back of samples using Micro TIG welder (Orion Pulse 250i)
- Angled sample holders were made of 316 stainless steel
- Aluminum foil shroud placed over crucible assembly to create aperture to reduce environmental radiation from reaching the camera

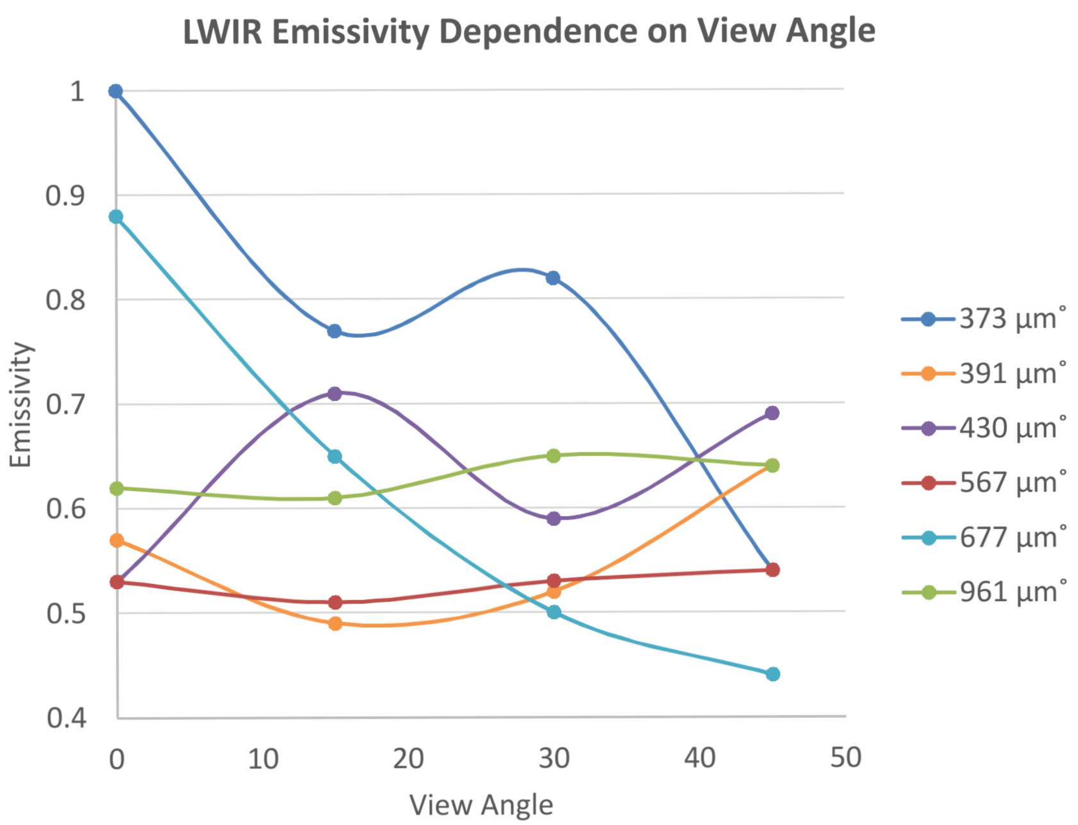


Emissivity Calculation

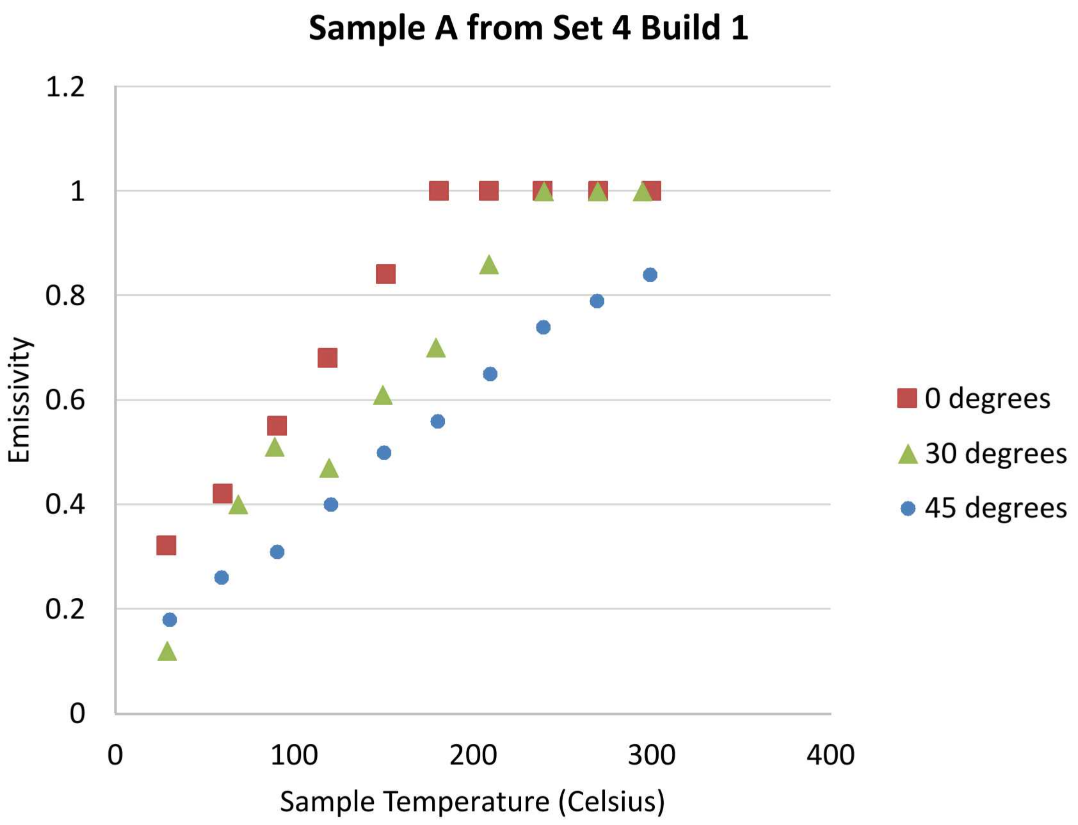
- Multiple images saved with MWIR camera with a range of emissivity values
- Average sample temperature calculated for each image
- Average sample temperature compared to surface thermocouple value
- MWIR image that minimized error between calculated and actual sample temperature was used to estimate emissivity value

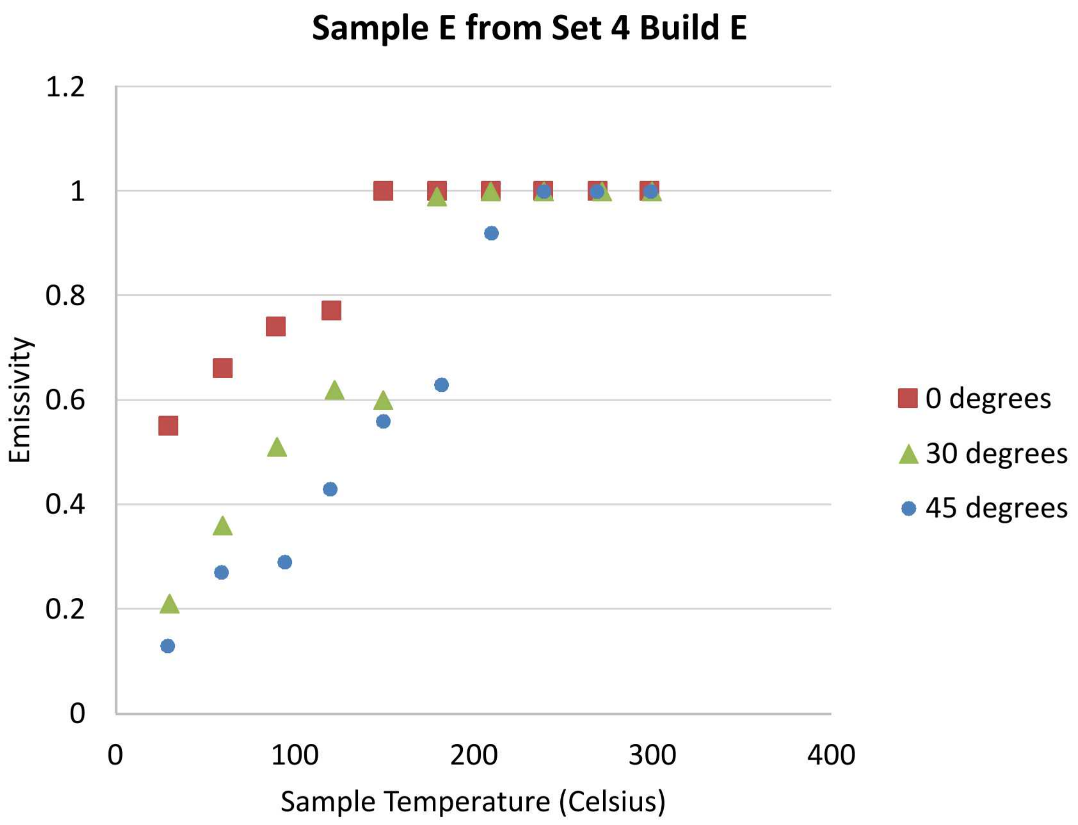
Room Temperature Results – No Window



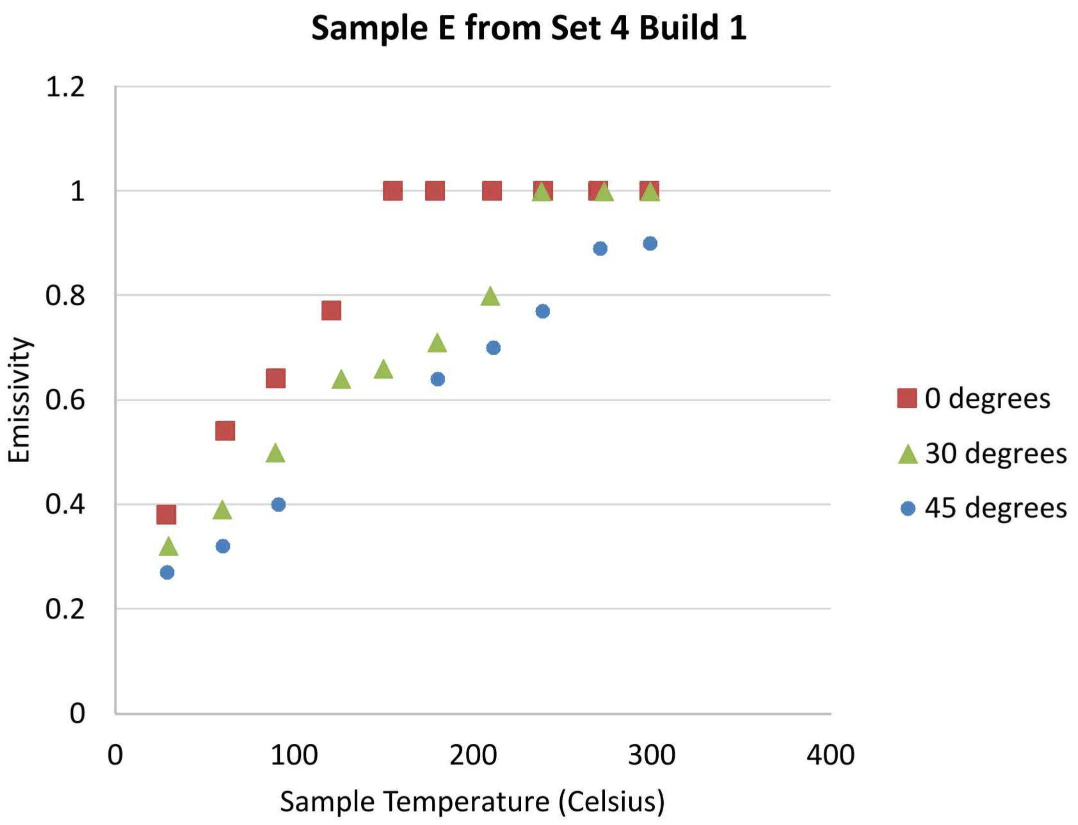


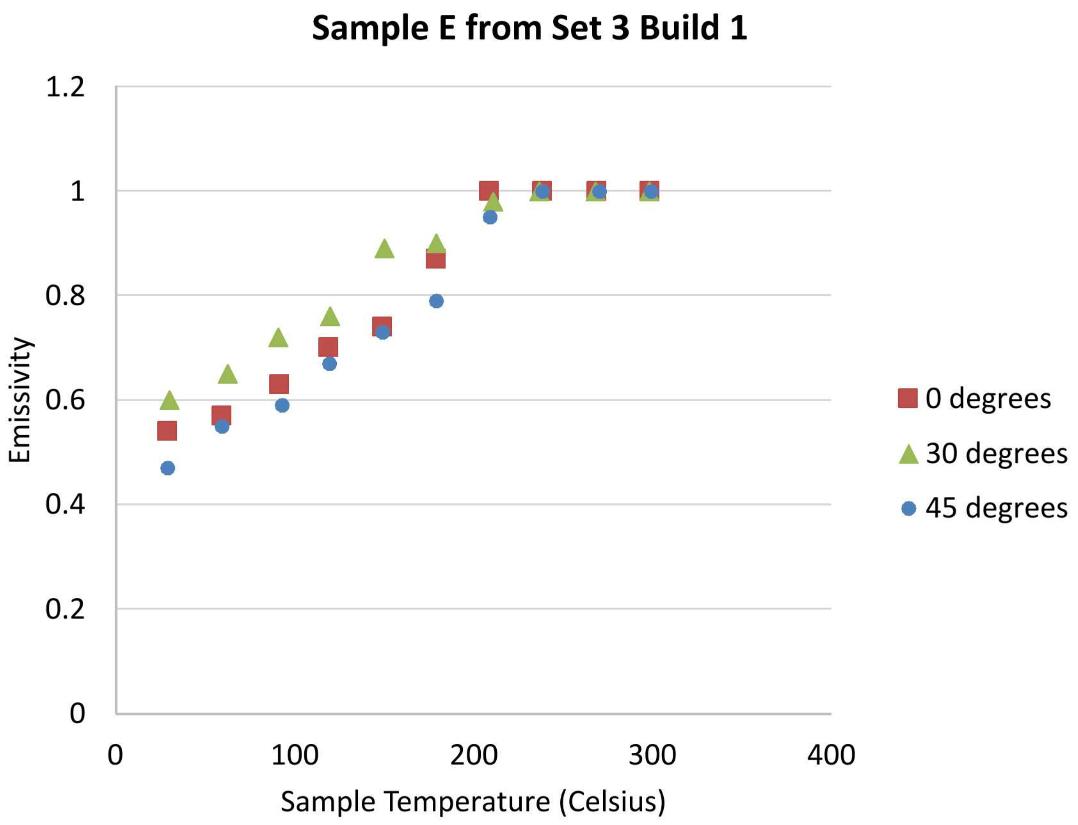
Elevated Temperature Results (MWIR only)





Elevated Temperature Results (MWIR only)





Task 2 Conclusions

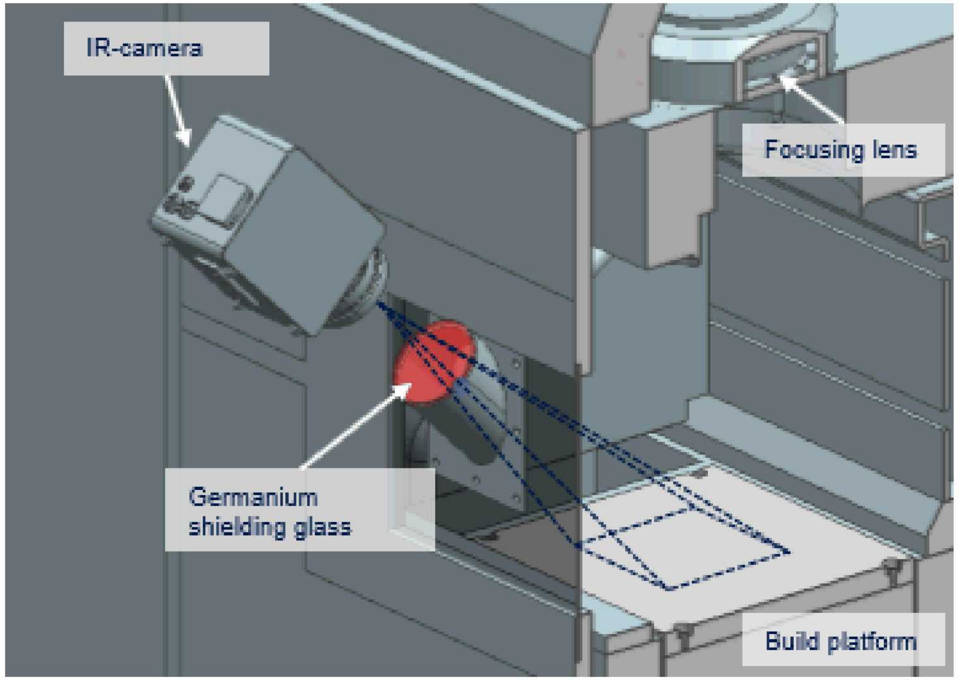
- As view angle increases, emissivity decreases
  - The rougher the surface, emissivity is less dependent on view angle(shadowing is not as effective)
- 45 degree angle minimizes emissivity differences
- After certain temperature threshold, differences in view angle are reduced – so not applicable at higher temperatures

Task 3: In-Situ Surface Roughness Measurements

- Purpose: to test capability of measuring surface roughness of as built AM surfaces in-situ
- Test viability of using in-situ measurements to adjust emissivity on a layer wise basis

Possible In-Situ SR Measurement Techniques

- Laser profilometry
- Raman Spectroscopy
- Moiré Profilometry
- Optical Coherence Tomography

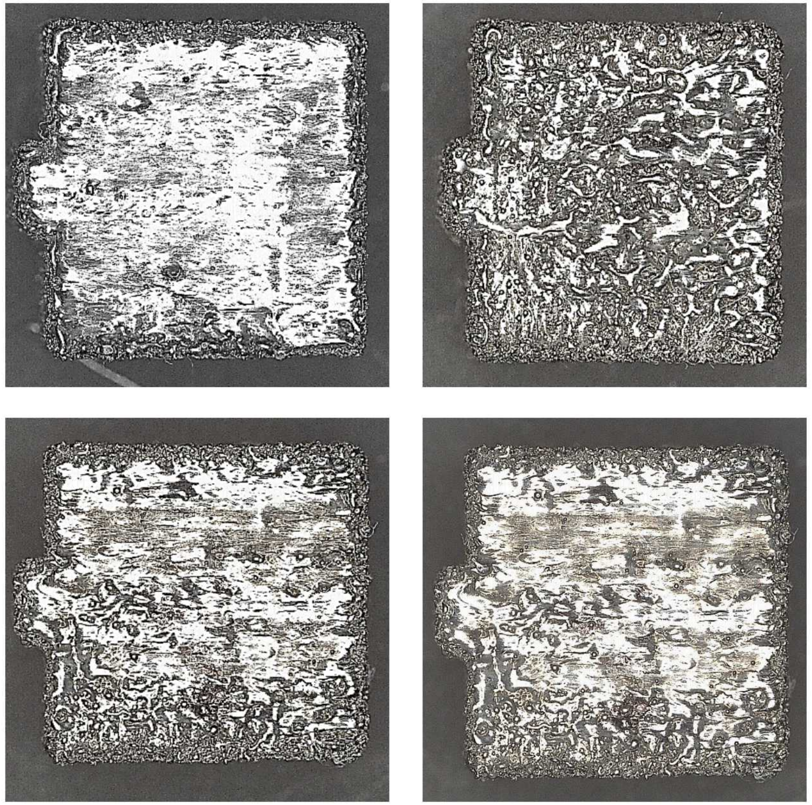


Optical Coherence Tomography (OCT)

- Time of flight differences creates interference pattern
- Ease of implementation
- LD-600 (Laser Depth Dynamics)
- Implemented on an Aconity Lab L-PBF research machine
- Experimental axial resolution: 25 microns

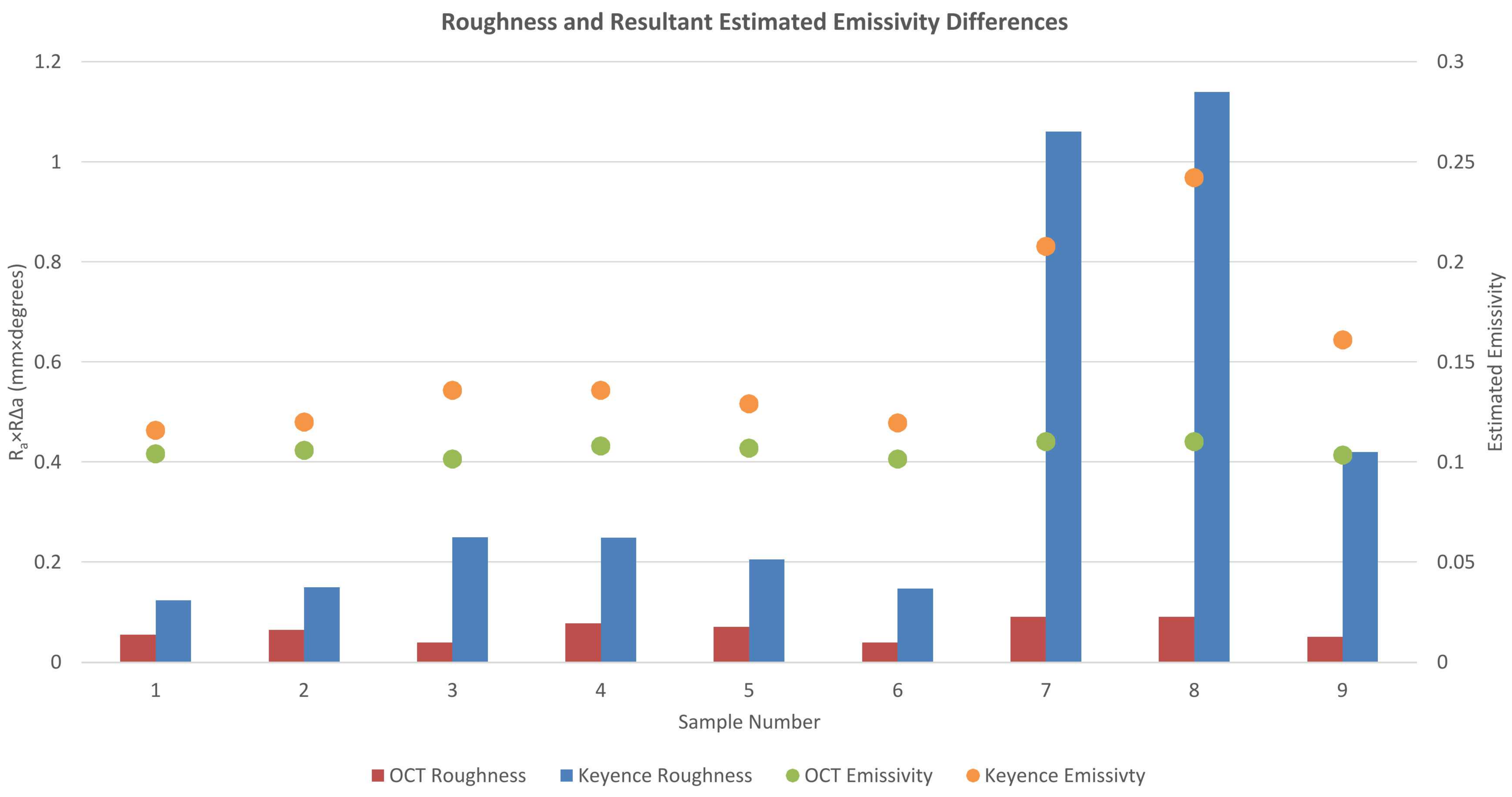
Experimental Design

- 1cm cubes were built with a range of process parameters
- OCT measurements taken on top surface of parts during build
- Fringe projection microscopy (FPM) measurements taken after the build with Keyence VR3100
- Measurements compared for resolution capabilities and emissivity estimations



Experimental Procedure

- OCT system at Lawrence Livermore used
- Parts shipped from Lawrence Livermore to Sandia for post-build measurements
- Top surface measured with OCT
- Measurements were compared with measurements gathered from Keyence VR3100 high resolution images


Roughness and Resultant Estimated Emissivity Differences
1.2
1
0.8
0.6
0.4
0.2
0
0.3
0.25
0.2
0.15
0.1
0.05
0
Ra×RΔa (mm×degrees)
Estimated Emissivity
1
2
3
4
5
6
7
8
9
Sample Number
OCT Roughness
Keyence Roughness
OCT Emissivity
Keyence Emissivty

Task 3 Conclusions

- Filtering causes aliasing of surface features, which reduces the accuracy of the measurements
- However, even for the roughest surfaces, the emissivity differences did not exceed .12
- Average deviation did not exceed .04
- The extremely rough surfaces would most likely not be produced during normal manufacturing

Overall Conclusions

- Geometric Optical Region
- $R_a \times R\Delta a$
- View angle increase = emissivity decrease
- 45 degree best view angle tested
- OCT measurement technique suitable for in-situ surface roughness measurements

Future Work

- Improve predictive ability for wider range of surface conditions and materials
- New materials
  - Aluminum, Titanium
- Look at effects of SR on other IR cameras
- Improve OCT Accuracy

Acknowledgements

- Sandia National Labs
  - Eric Forrest
  - Allen Roach
  - Jeremy Wright, Josh Koepke, David Said, Bradley Jared, Josh Stanford
- Lawrence Livermore Labs
  - Nick Calta
- UT Austin

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Questions?

Surface Roughness Relationship with Emissivity

Case 1: $R_q/\lambda << 1$

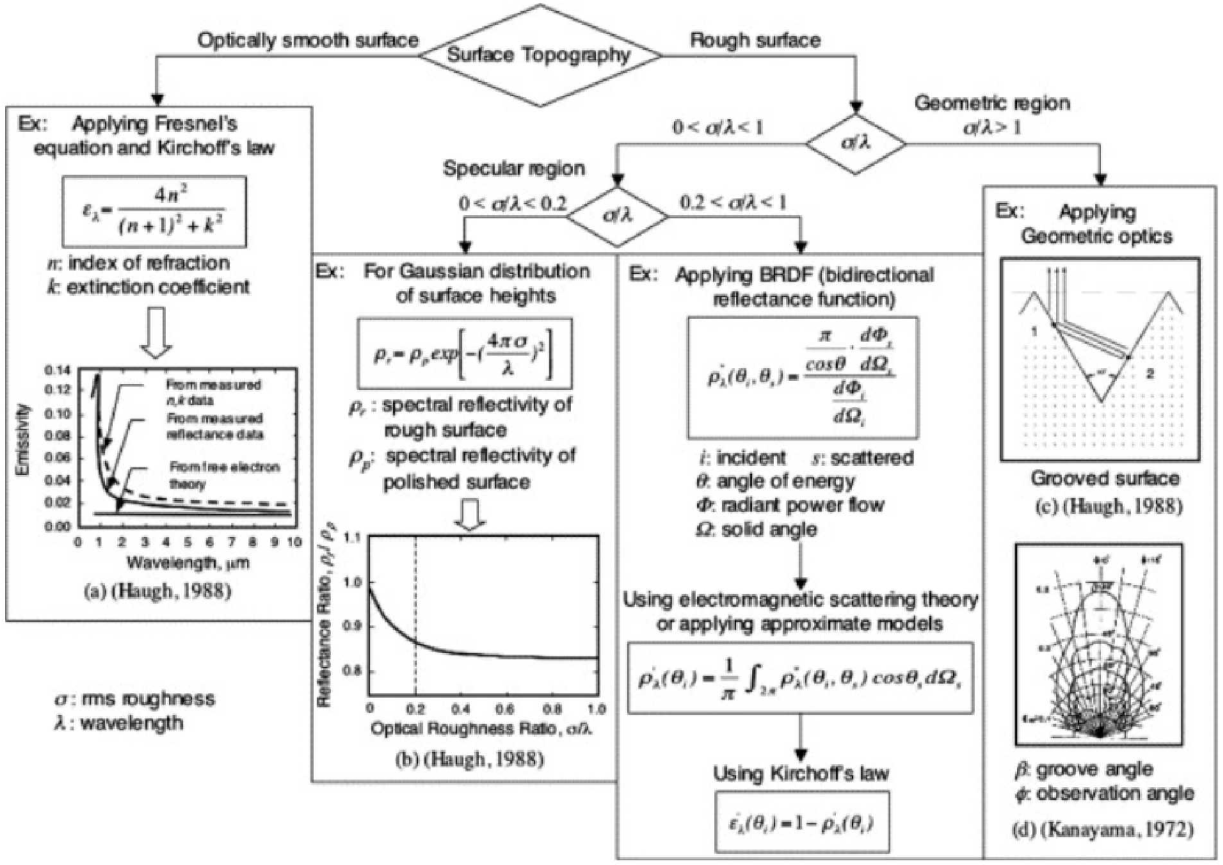
- Optically smooth surface, where the roughness of the surface does not contribute to the thermal emissivity of the object.

Case 2: $0.2 < R_q/\lambda < 1$

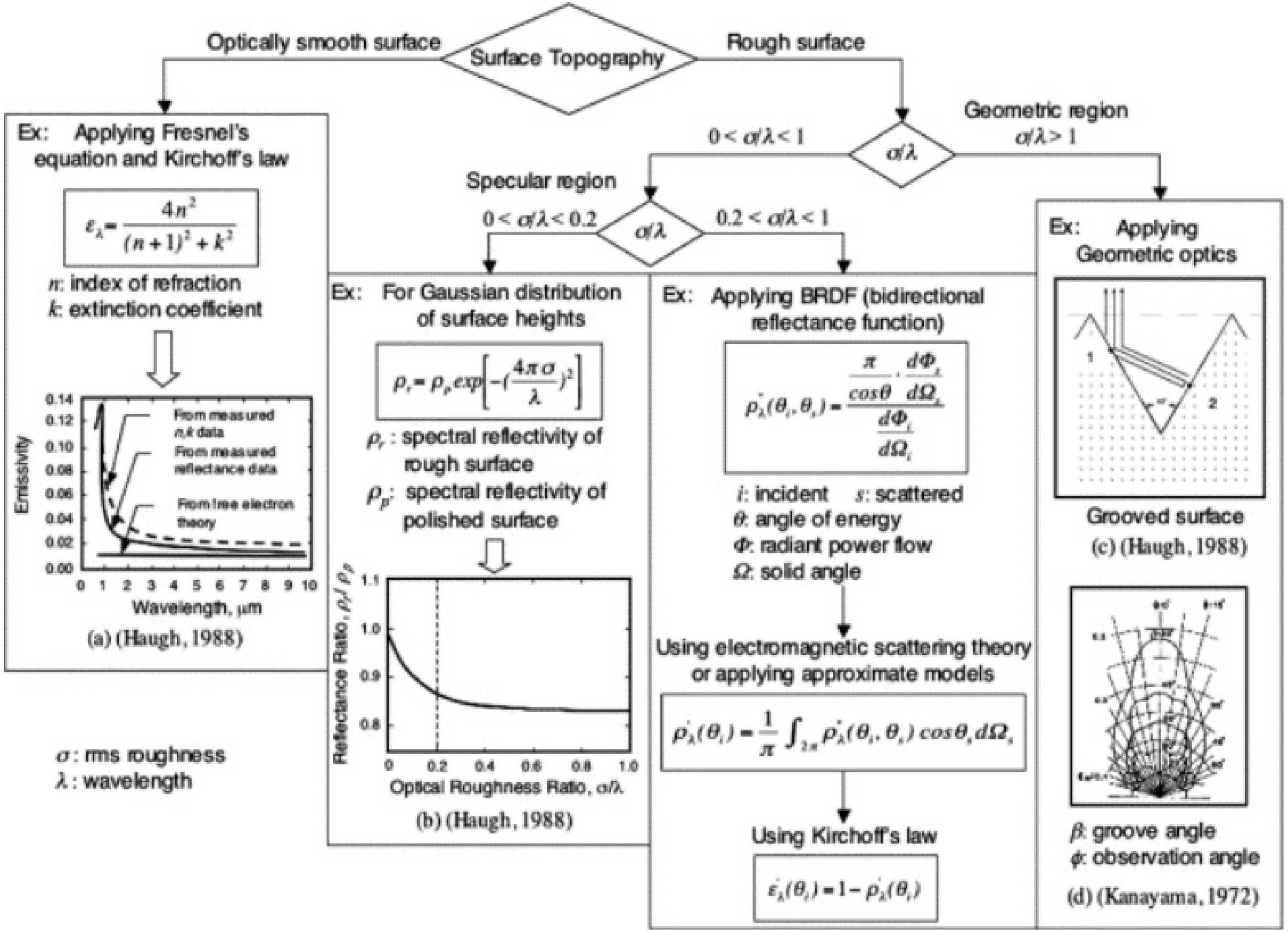
- Intermediate region where there is no easy defined relationship between emissivity and surface roughness. The roughness of the surface does contribute but is not solely responsible for affecting the emissivity.

Case 3: $1 < R_q/\lambda$

- The geometric region, where it is suggested that the slope of the peaks and valleys of the surface can play a key role in emissivity trends.

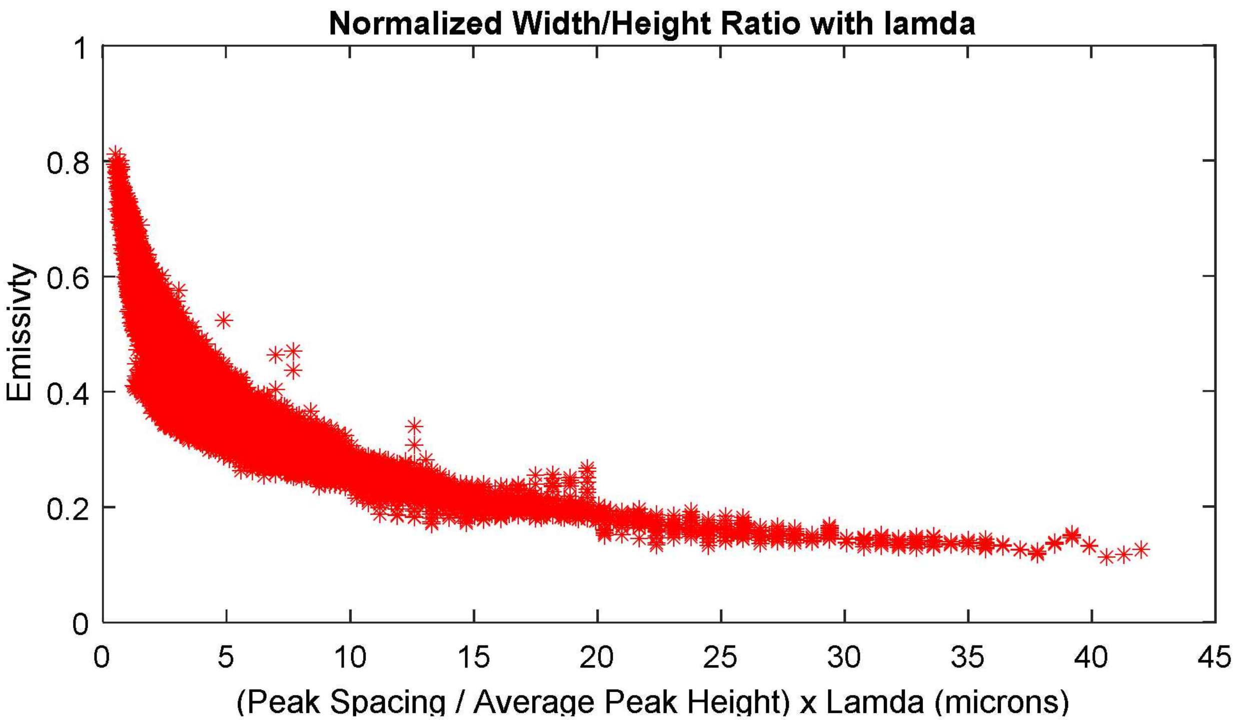


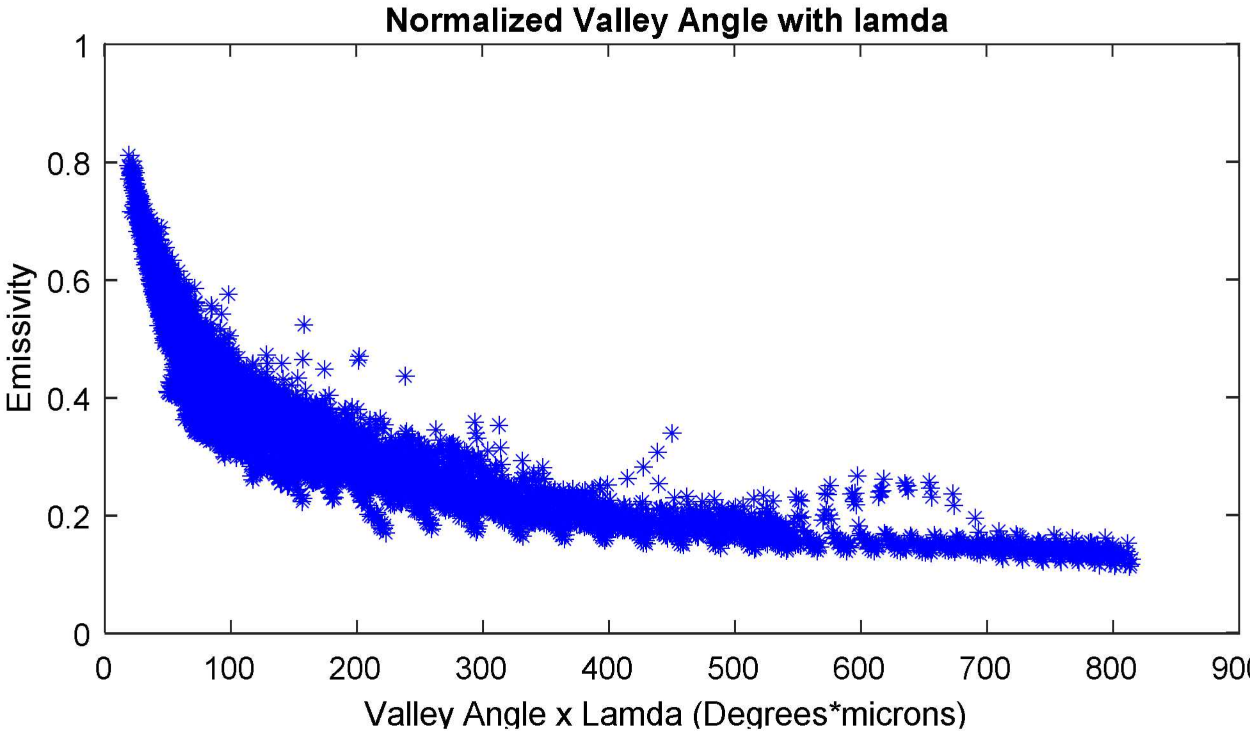
Sourced from: Wen and Mudawar, "Modeling the Effects of Surface Roughness on the Emissivity of Aluminum Alloys"



Sourced from: Wen and Mudawar, "Modeling the Effects of Surface Roughness on the Emissivity of Aluminum Alloys"

Skewed Triangles Results



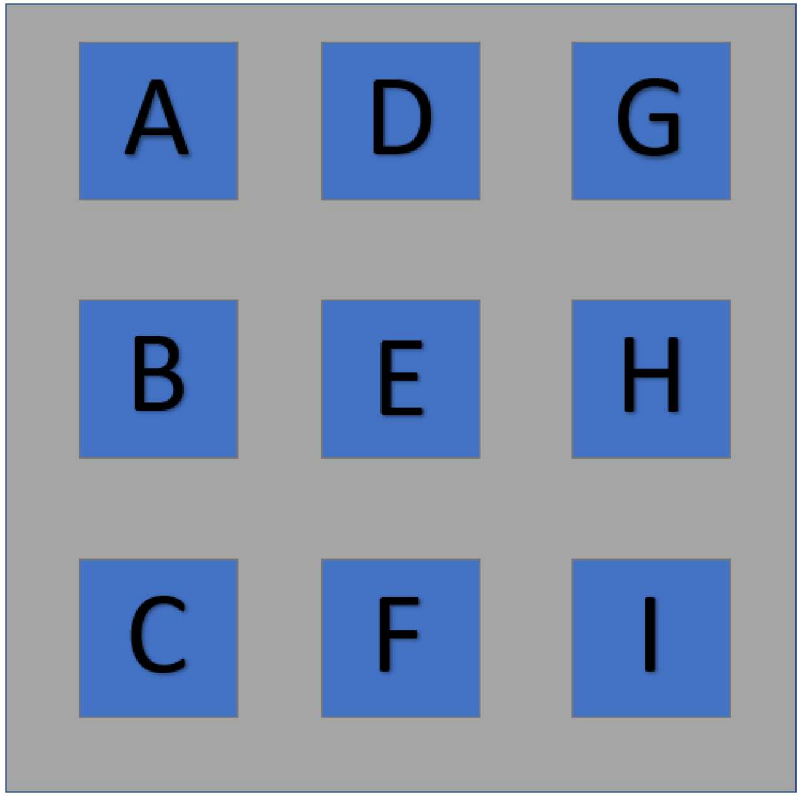


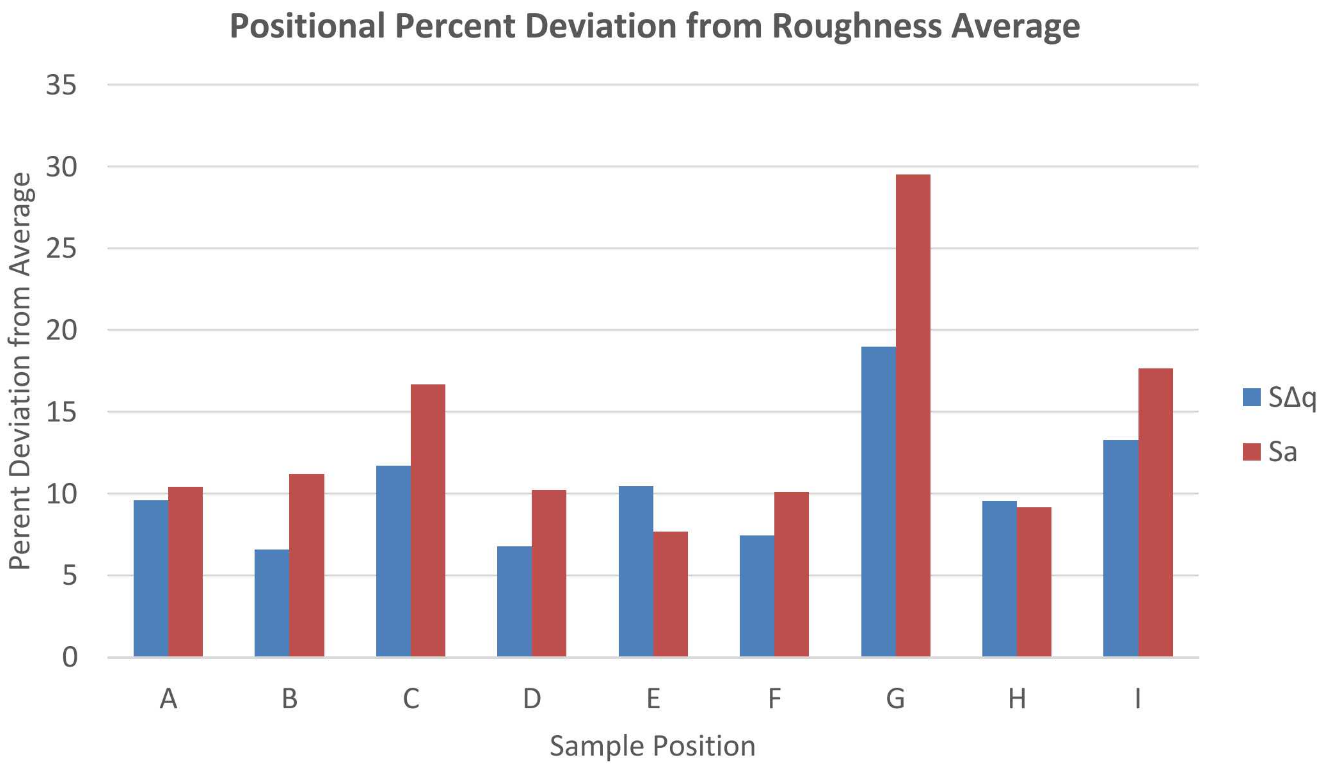
Surface Roughness Measurement Technique Comparison

- Keyence consistently reads rougher, showing possible aliasing of Dektak

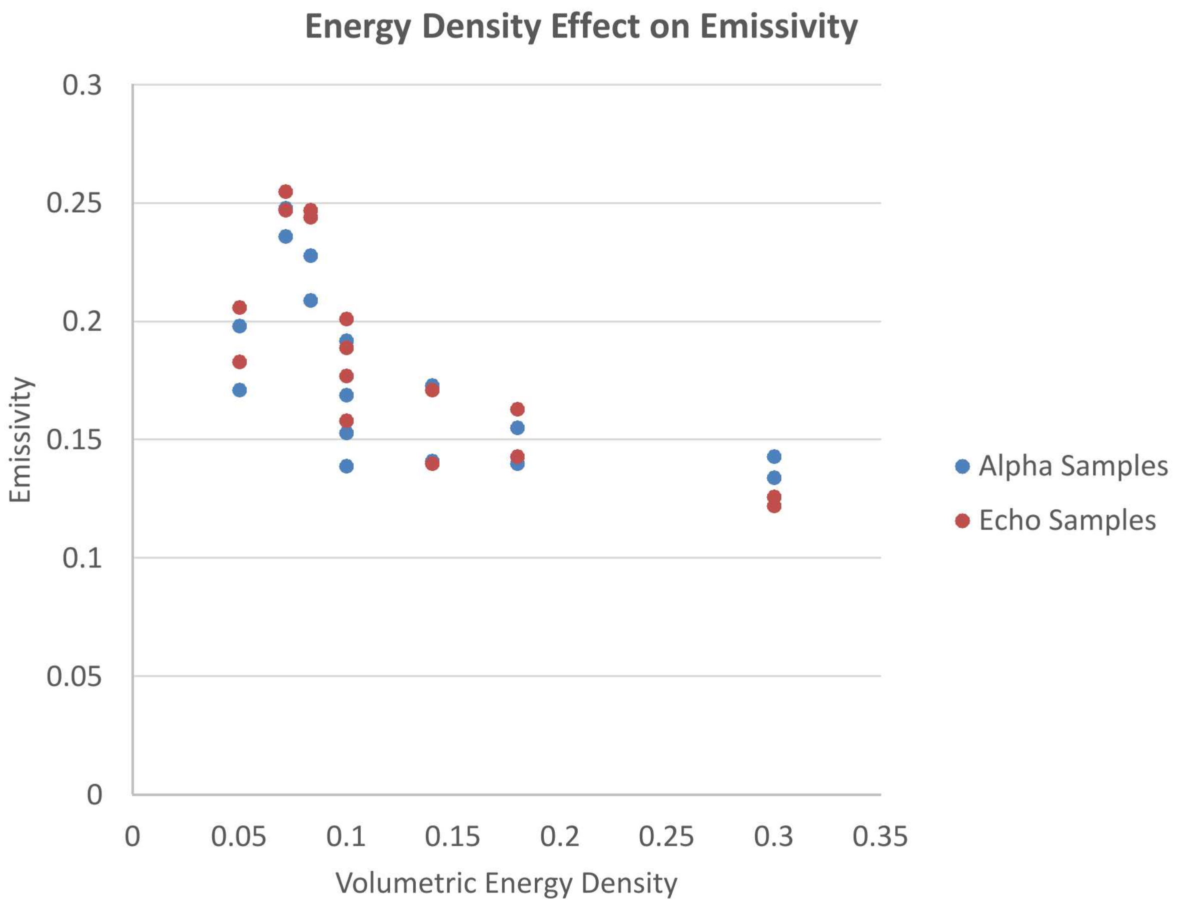
	LENS milled			LENS glazed			DMLS A			DMLS B			DMLS Milled A			DMLS Milled B		
	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference
Ra (µm)	3.390	0.642	2.748	2.020	0.567	1.453	6.970	7.402	-0.432	9.790	6.429	3.361	1.570	1.813	-0.243	1.380	1.705	-0.325
Rq (µm)	4.130	0.744	3.386	2.530	0.677	1.853	8.720	9.029	-0.309	12.500	8.646	3.854	1.970	2.262	-0.292	1.750	1.992	-0.242
			3.067			1.653			0.371			3.607			0.268			0.284
															Average Difference:			1.542

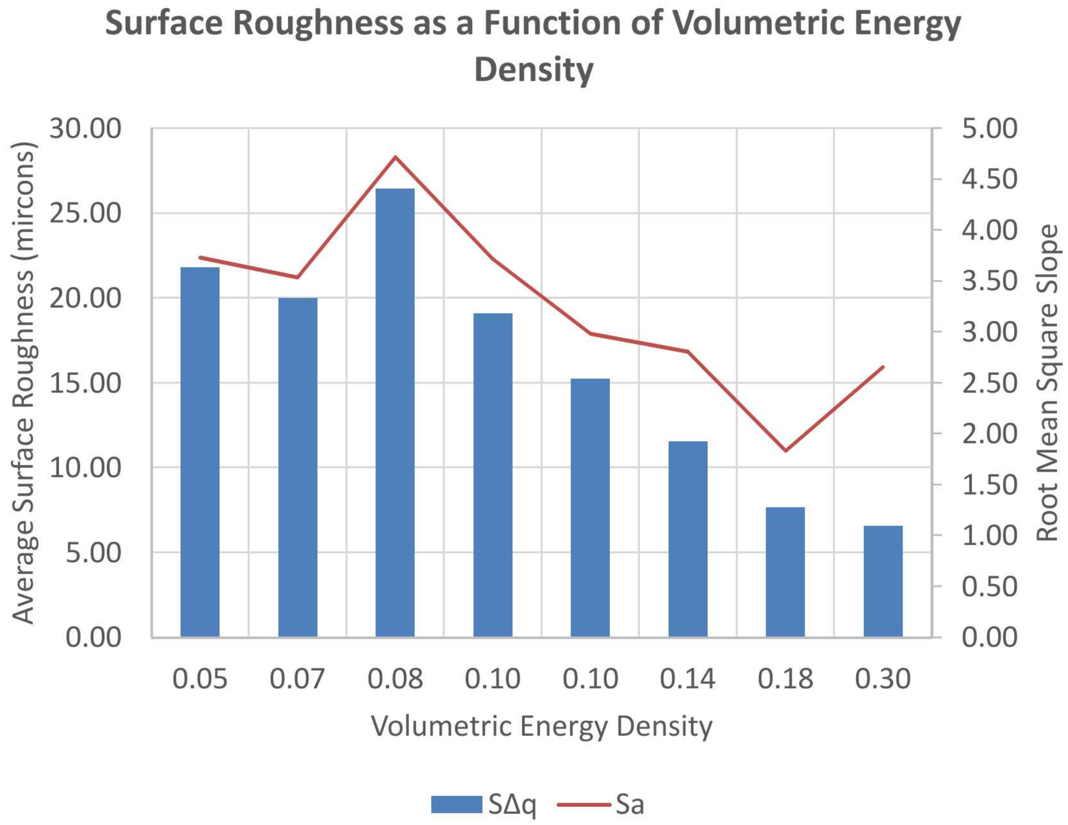
Positional Dependence of SR





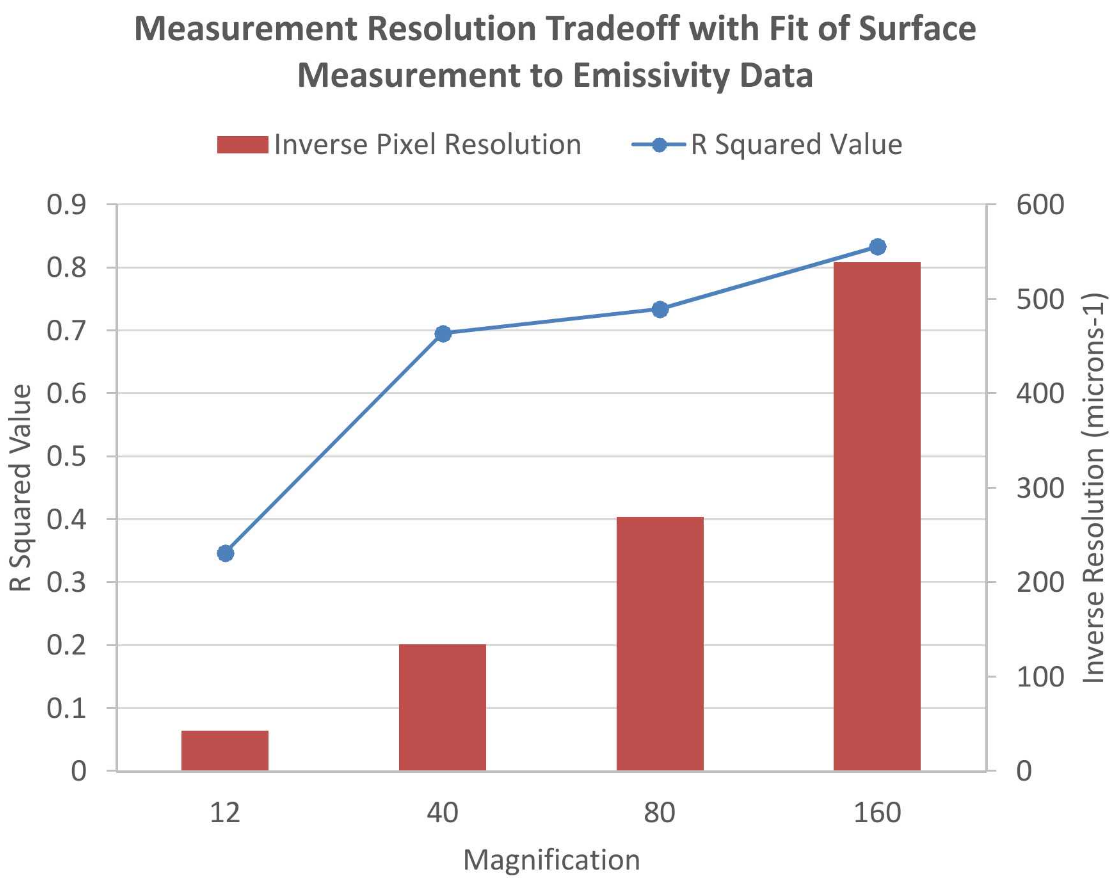
Emissivity Measurements



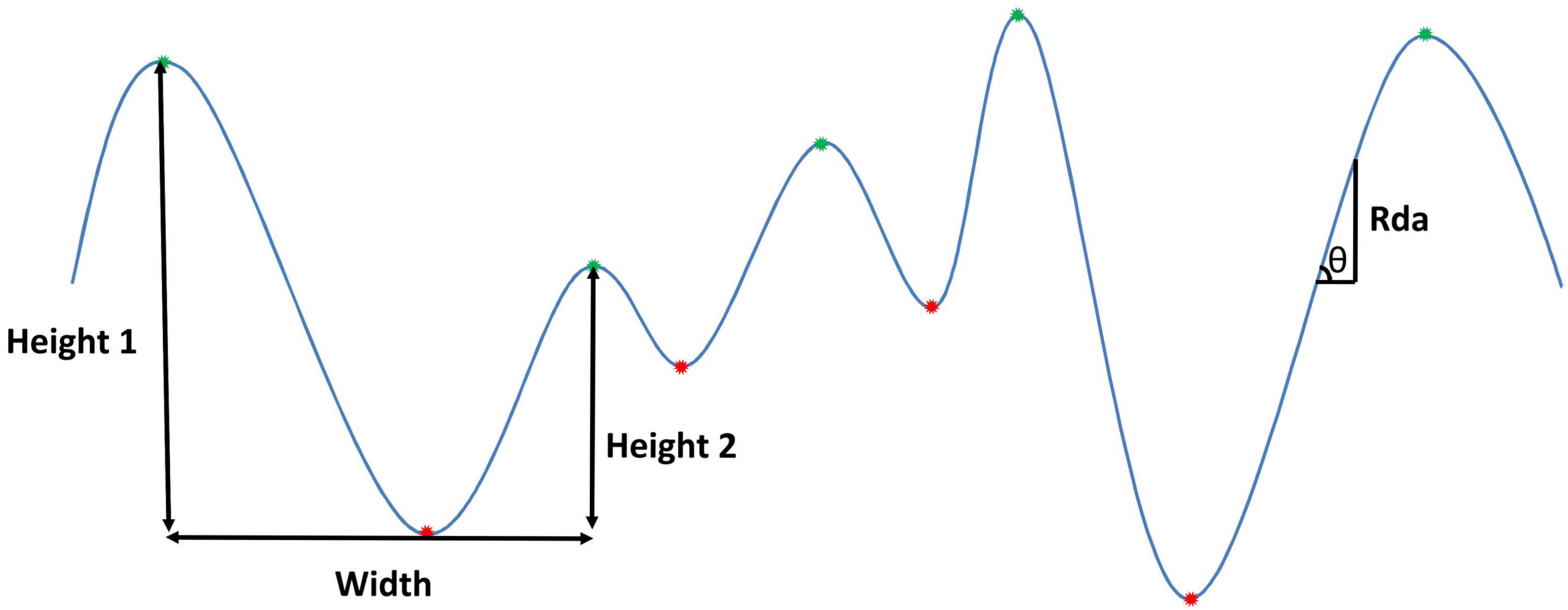


Measurement Resolution Importance

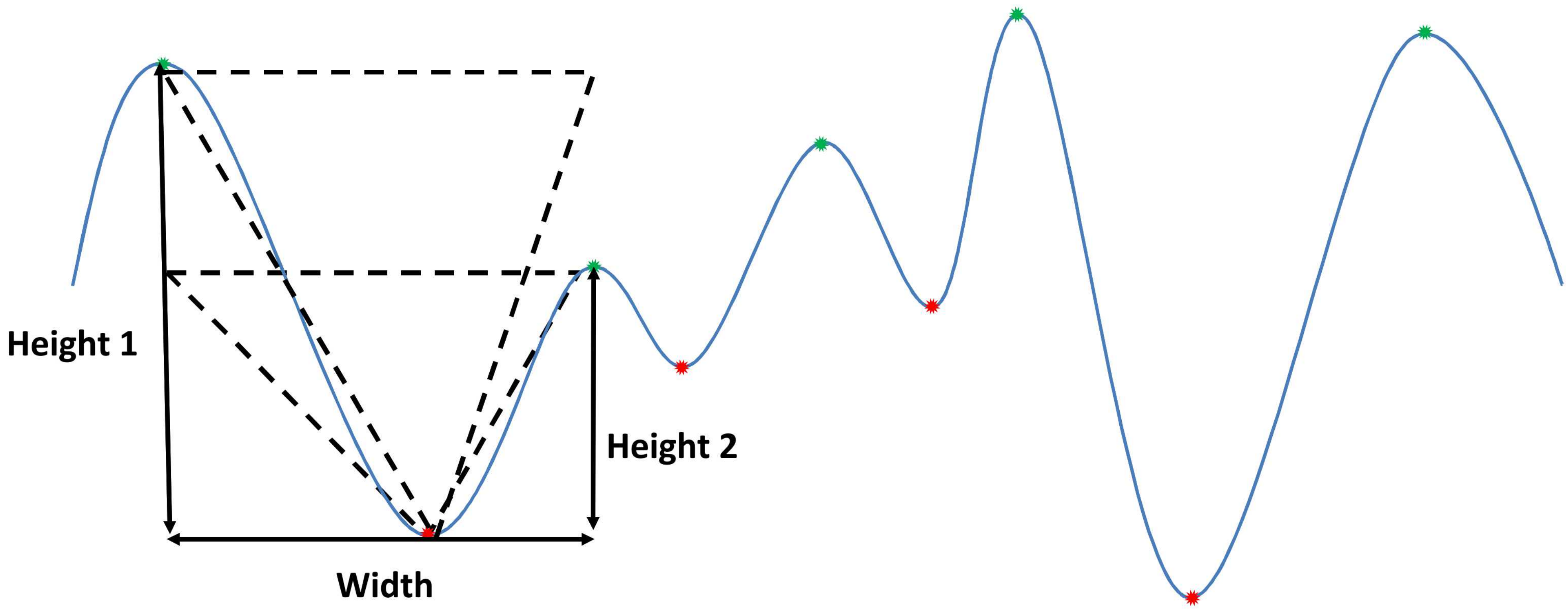
- Resolution of surface roughness measurements had a large effect on correlation strength to emissivity
- Measurement spacing did not affect correlation strength



Valley Measurements



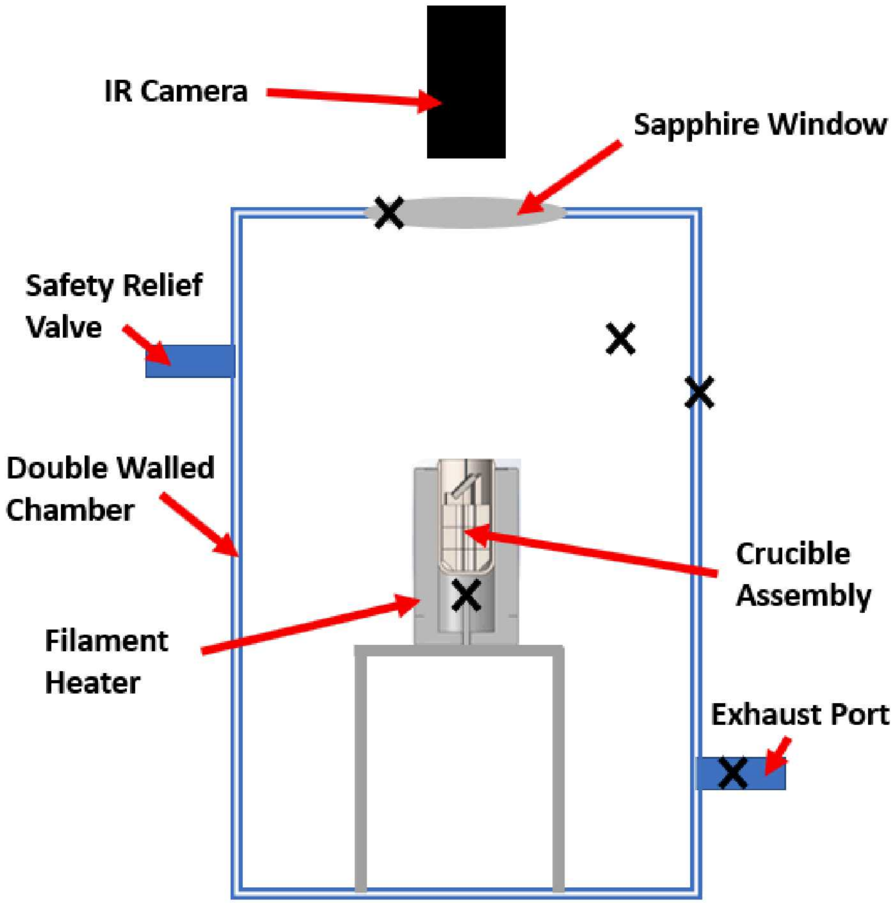
Valley Angle Calculation



Unusual Surface Feature Effects

- Vertical walls – just insert into calculation as really tall slope
- Partially or completely un-sintered particles that create overhangs
  - Does increase, but difficult way to measure in-situ
  - Outside of scope – future studies w/ XCT
- Effects of oxidation/method of storing samples before vacuum furnace – all samples were stored under same conditions

Vacuum Furnace Set Up



OCT Estimation Error Quantification

$$E_1 = \varepsilon_1 \sigma {T_1}^4 \rightarrow E_1 = \varepsilon_2 \sigma {T_2}^4$$

- .12 emissivity difference
  - 300 K → 65 degrees error
  - 1073 K → 233 degrees error
- .04 emissivity difference (total average)
  - 300 K → 26 degrees error
  - 1073 K → 94 degrees error

Publication Plan

- At least 2 Journal Articles
  - Emissivity vs SR (Simulations and then Experimental validation)
  - OCT in-situ SR measurements
- 2 conference papers
  - SFF 2019
  - Angular effect on observed emissivity

Repeatability/Uncertainty

HDR – Emissivity Measurements

- 10 measurements on AL6061 sample

  $\bar{x} = .237 \quad \sigma = .0027$ (~1%)
- Standard uncertainty = $\bar{x}/\sqrt{n} = 8.5\text{e-}4$

Keyence Surface Measurements

- R_a – std dev is .17% of measurement
- R_{rms} – std dev is .25% of measurement
- RΔa – std dev is .16% of measurement
- RΔq – std dev is .79% of measurement

- u_B= 1.80 microns

Simulations

- Used for searching trends and relative nature
- Didn’t use absolute values from simulations for any purpose

Vacuum Furnace Measurements

- Atmospheric control of the lab
  - 23 +/- 1˚ Celsius
  - 40 +/- 5% Relative Humidity
- MWIR camera – unable to estimate due to inability to propagate input uncertainties to emissivity since conversion equation is unknown
- Thermocouples +/-2.2˚C uncertainty
  - Translates to standard deviation of .02 emissivity value

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