Faculty of Engineering and Physical Sciences

Aeronautics, Astronautics and Computational Engineering

Structural effects on the high temperature performance of the Super High Temperature Additive Manufactured Resistojet (STAR)

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Current State of the Project

- Manufactured through Selective Laser Melting (SLM)
  - 316L Stainless Steel
  - Nickel alloys (LEO requirements)
  - Refractory metals (GEO requirements)
- Recirculating flow geometry
- 300µm typical wall thickness
- No post processing due to closed design

STAR Performance vs. Simulation

- Initial attempts to match Multiphysics simulations to experiments show large deviations in temperature
- Believed to be due to poorly understood variations in materials properties and as-manufactured geometries
  - Emissivity
  - Resistivity

Emissivity and Resistivity

- Resistivity
  - Measure of a materials inherent resistance to the flow of current

- Influenced by
  - Temperature
  - Lattice structure
  - Impurities

- Emissivity
  - Measure of emissive power of a surface at a specific temperature

Emissivity and Resistivity

- Resistivity
  - Measure of a materials inherent resistance to the flow of current

- Emissivity
  - Measure of emissive power of a surface at a specific temperature

- Influenced by
  - Surface features
    - Surface treatments
    - Roughness

Selective Laser Melting – Physical Phenomena

- Powder bed laser melting additive manufacturing process
- Layered process results in rough surfaces through several mechanisms
  - Build angle
  - Layer thickness
  - Laser properties
- Increased cooling rate causes finer grain structure

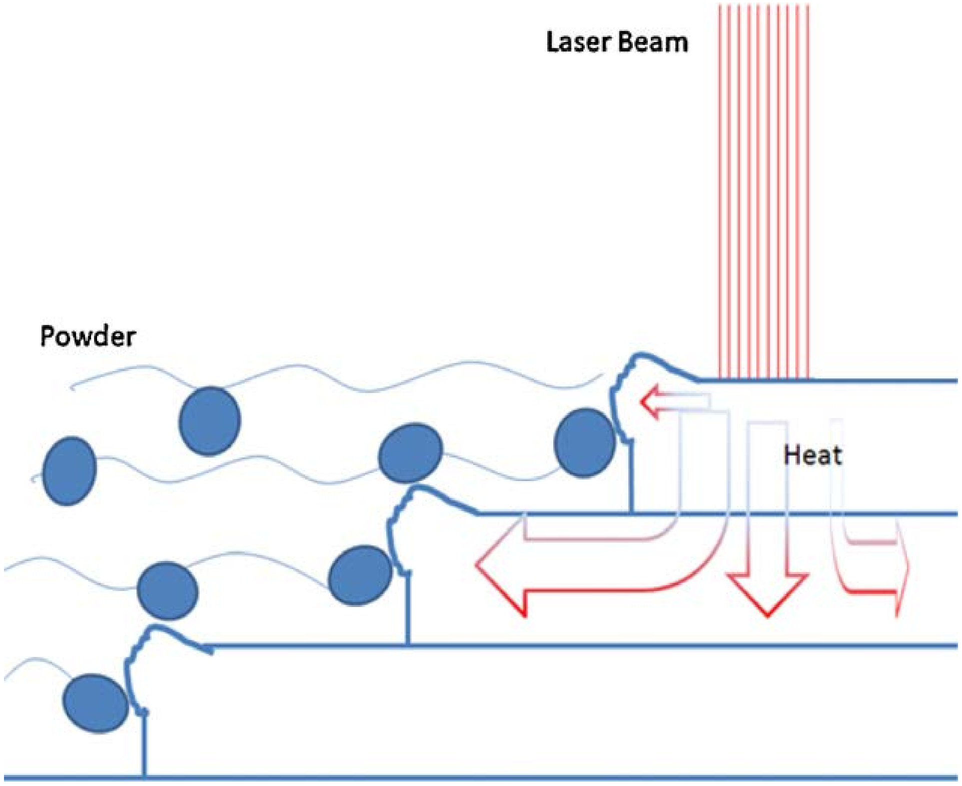


Diagram of heat diffusion and roughness sources in SLM process [2]

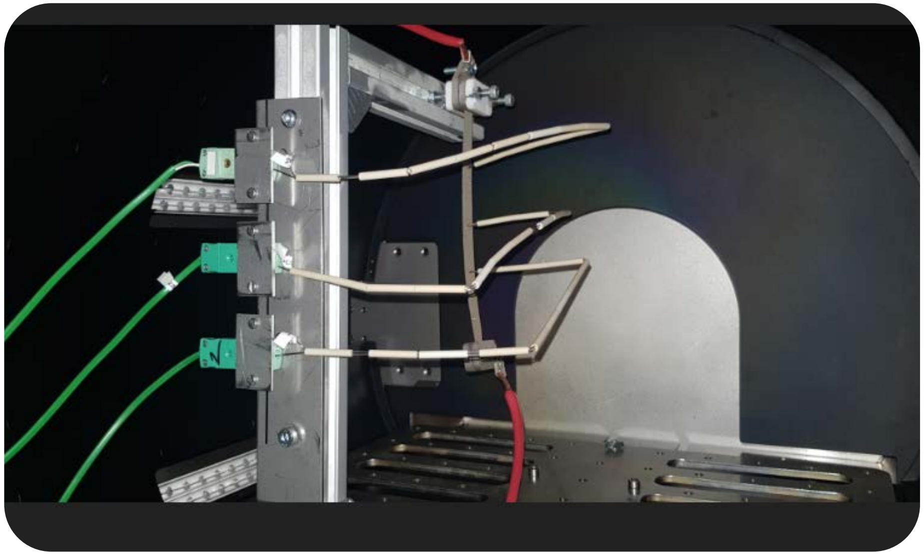
[2] G. Strano, L. Hao, R. M. Everson, and K. E. Evans, "Surface roughness analysis, modelling and prediction in selective laser melting," *J. Mater. Process. Technol.*, vol. 213, no. 4, pp. 589–597, 2013.

Goals of this research

- Accurately measure resistivity and emissivity of as-built SLM parts
- Validate models against experimental data
- Apply models to resistojet simulations

Methodology

- ASTM Standard C835-06
- Total hemispherical emissivity
- Test strip resistively heated under vacuum
- Thermocouples measure surface temperature
- Thermocouples tapped to measure voltage

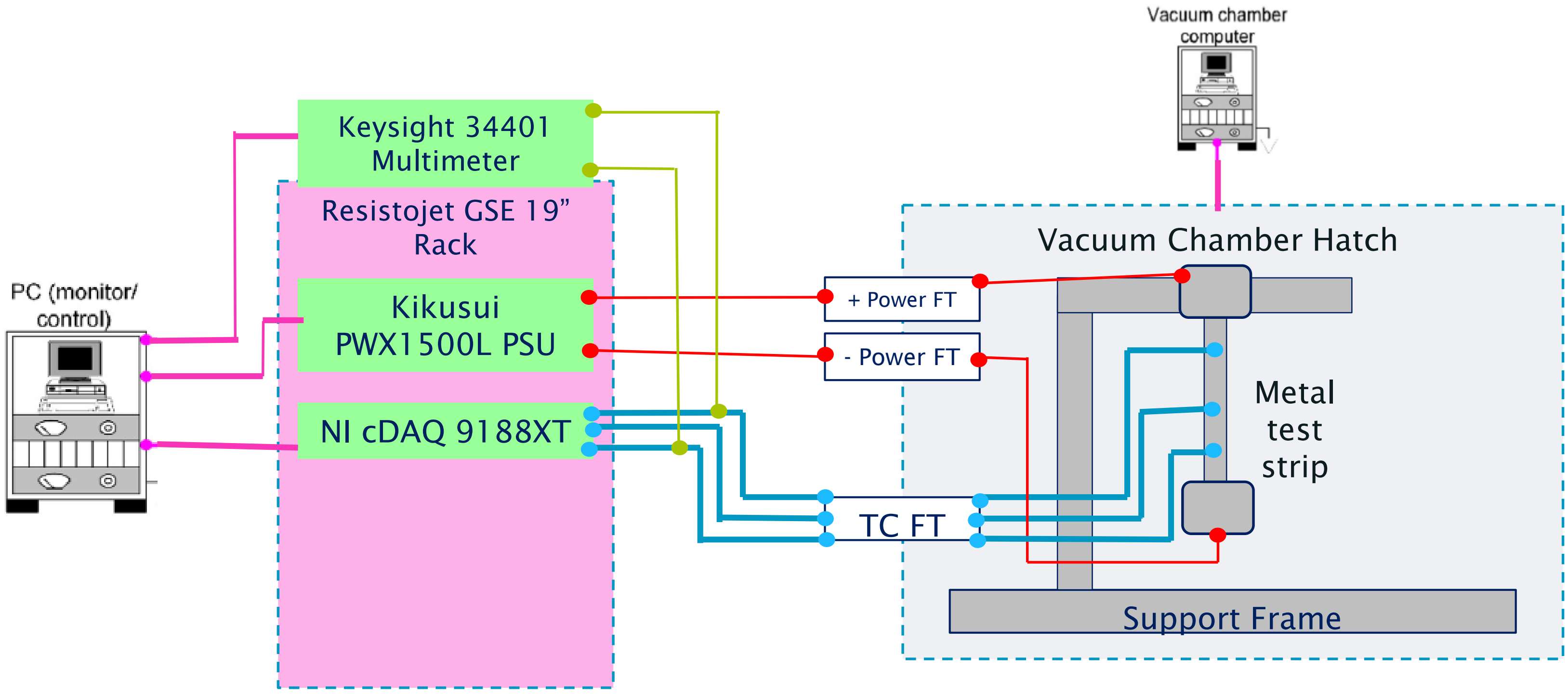


$$\epsilon = \frac{Q}{\sigma A_1 (T_1^4 - T_2^4)}$$

$$\rho = \frac{RA}{L}$$

Test Setup

- Test performed in small hatch of vacuum chamber (0.75m x 0.75m)
  - Thermal shroud acts as blackbody surface
  - Test performed at 10^{-5} mbar
- Three K-type thermocouples spot-welded to test strip surface 37.5mm apart
  - Diameter ~ 0.9mm
  - Fourth thermocouple attached to shroud wall
- Program controlled through LabVIEW



Materials & Process Parameters

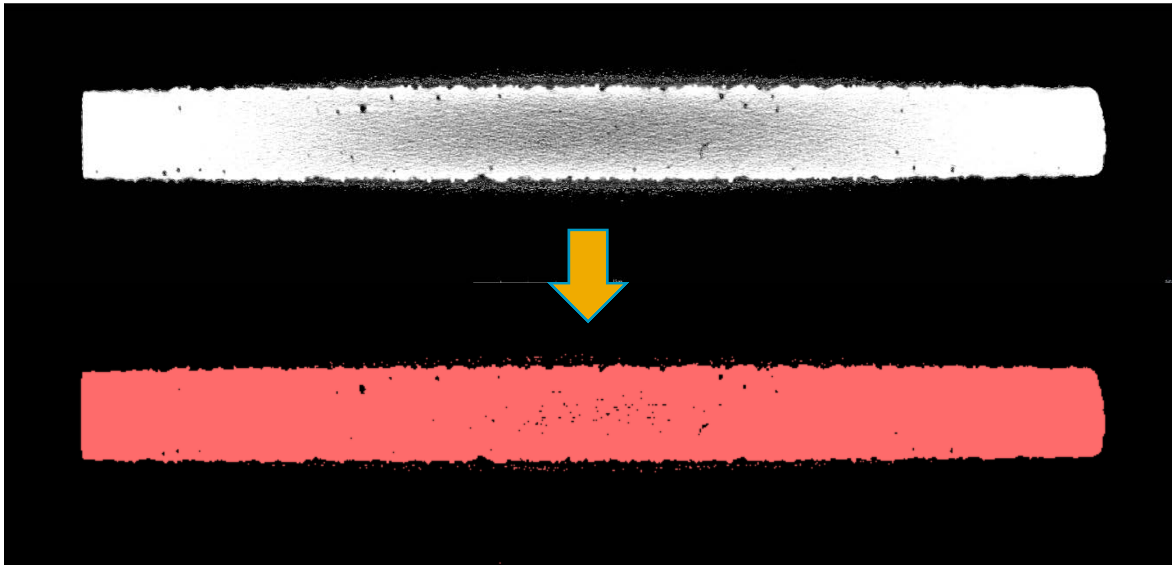
Property	Value	
Machine	Concept Laser M2 Cusing	EOS M270
Material	316L	Inconel 718
Laser Power (W) (Rated)	200	200
Laser Power (W) (Effective)	177	~180
Laser beam diameter (µm)	50	40
Layer thickness (µm)	30	30
Scan speed (ms^{-1})	7	>1
Hatch (mm)	5	-
Hatch pattern	Square Islands	-
Gas	N_2	-
Sample Width (mm)	13	10
Sample Thickness (mm)	0.25	1
Sample Length (mm)	200	200

Surface Evaluation

- Scanning Electron Microscopy
  - Performed using a JSM 6500F field emission Scanning Electron Microscope
  - Measurements taken at x50 and x330 magnification
- Focal Variation Microscopy
  - Performed using Alicona InfiniteFocus
  - Compares optical path difference between real and reference surface
  - Profile and areal roughness data

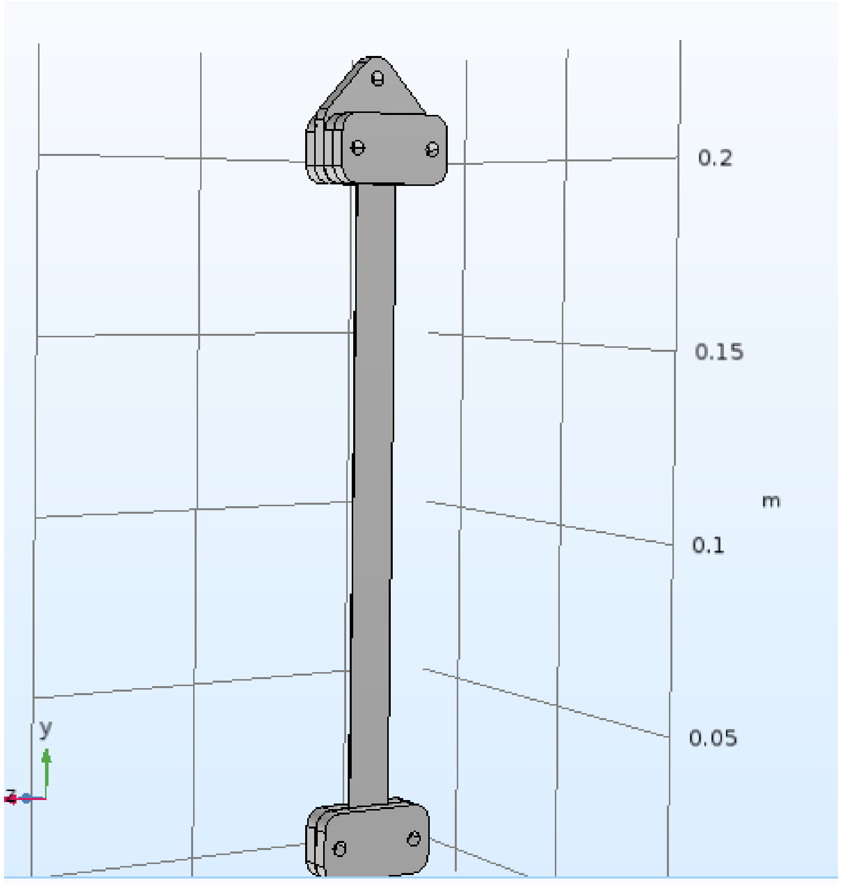
CT Scans – Area measurements

- Resistivity calculation requires accurate cross-sectional area
- Coupons CT-scanned using custom 450kVp / 225kVp Hutch system at µ-vis centre at Southampton
  - 2000 images taken over 15mm length in centre
- Radiographs made binary and cross-sectional area measured in ImageJ using particle size analysis



COMSOL Multiphysics Simulation

- Full 3D model of test setup
  - Electric current and Heat transfer packages
- Parametric sweep of stationary solutions to simulate steady-state
- Average cross sectional area of CT scan used as cross sectional area of test coupon

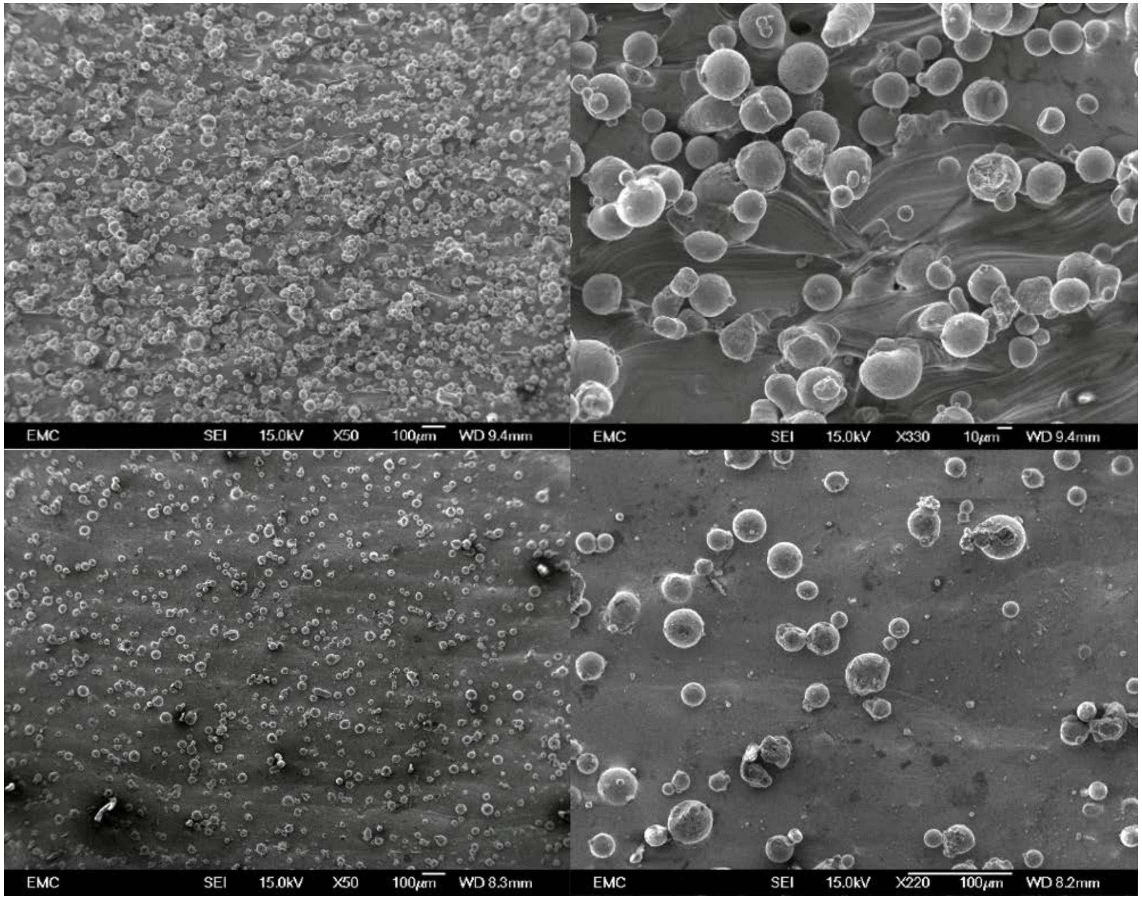


Results – Surface Inspection (SEM & FV)

x50 magnification | x330 magnification

316L Stainless Steel

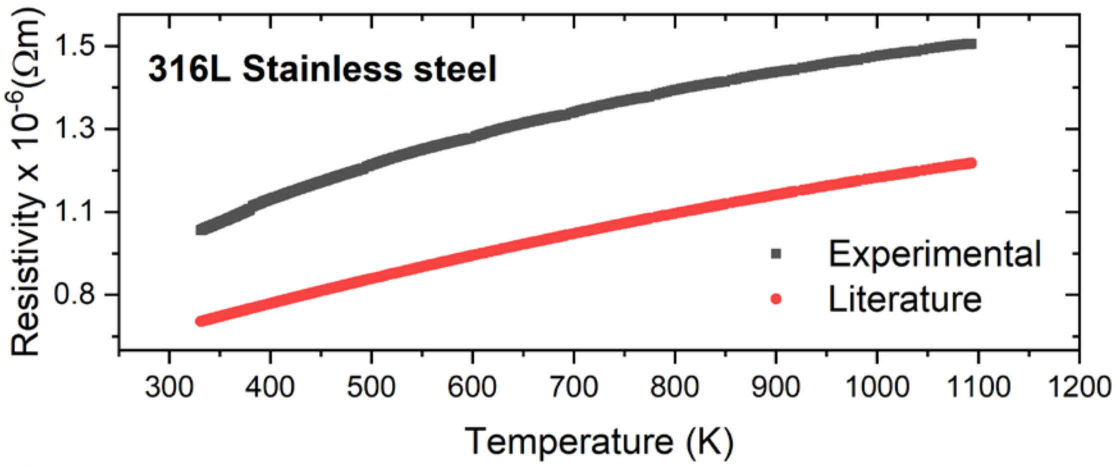
Inconel 718

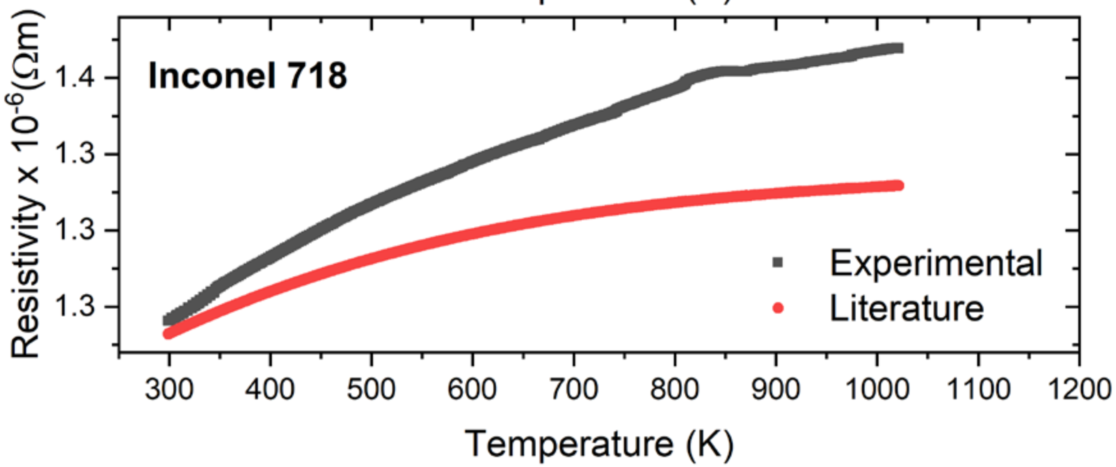


Material	Ra(µm)	Rq(µm)	Sa(µm)	Sq(µm)
Inconel 718	6.9	9.3	7.1	9.6
316L SS	21.4	26.0	-	-

Resistivity Results – Additive vs Traditional

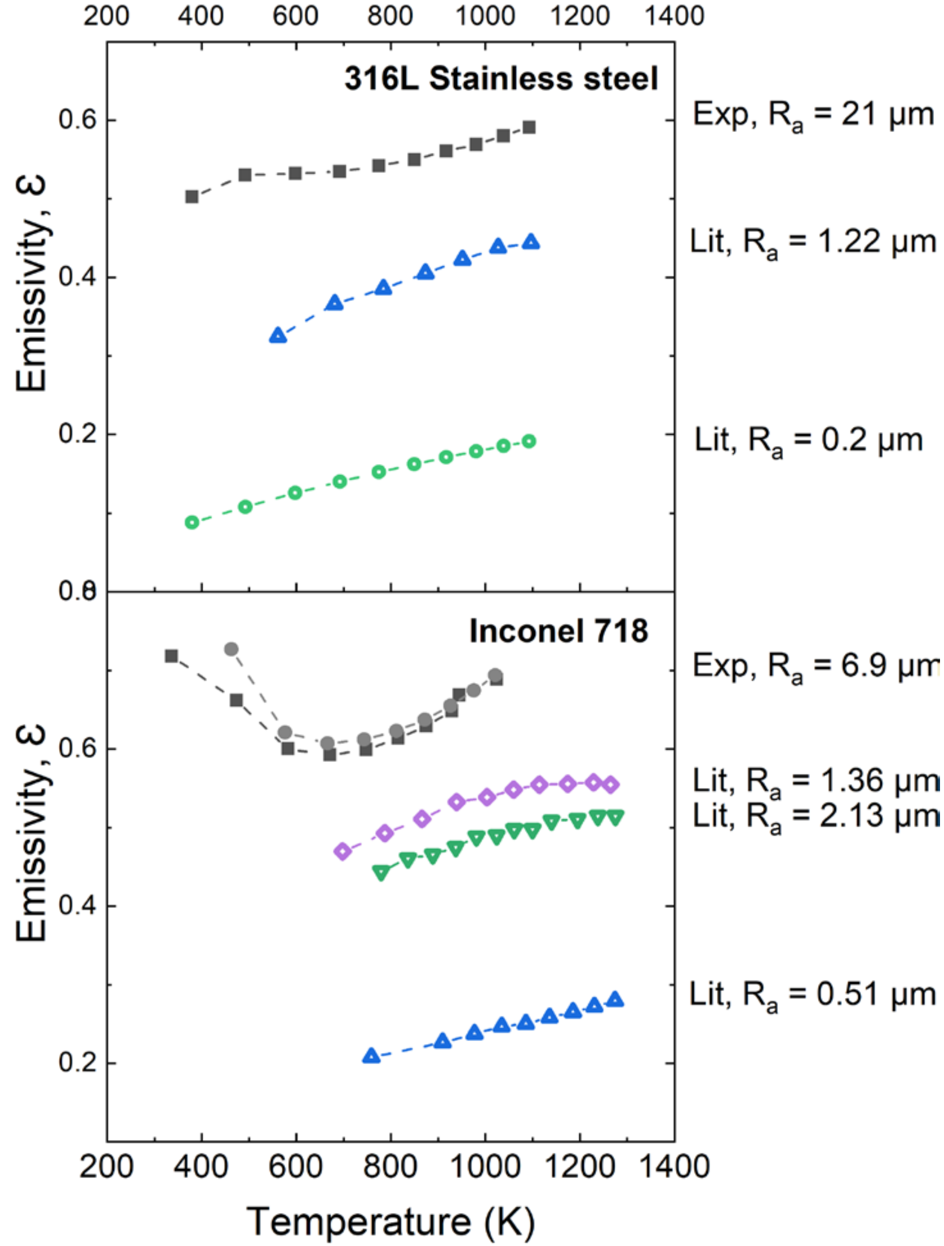
- SLM results for SLM materials higher than cast
- 316L Stainless Steel
  - ~ 20% difference over whole temperature range
- Inconel 718
  - ~ 2% difference at highest temperature





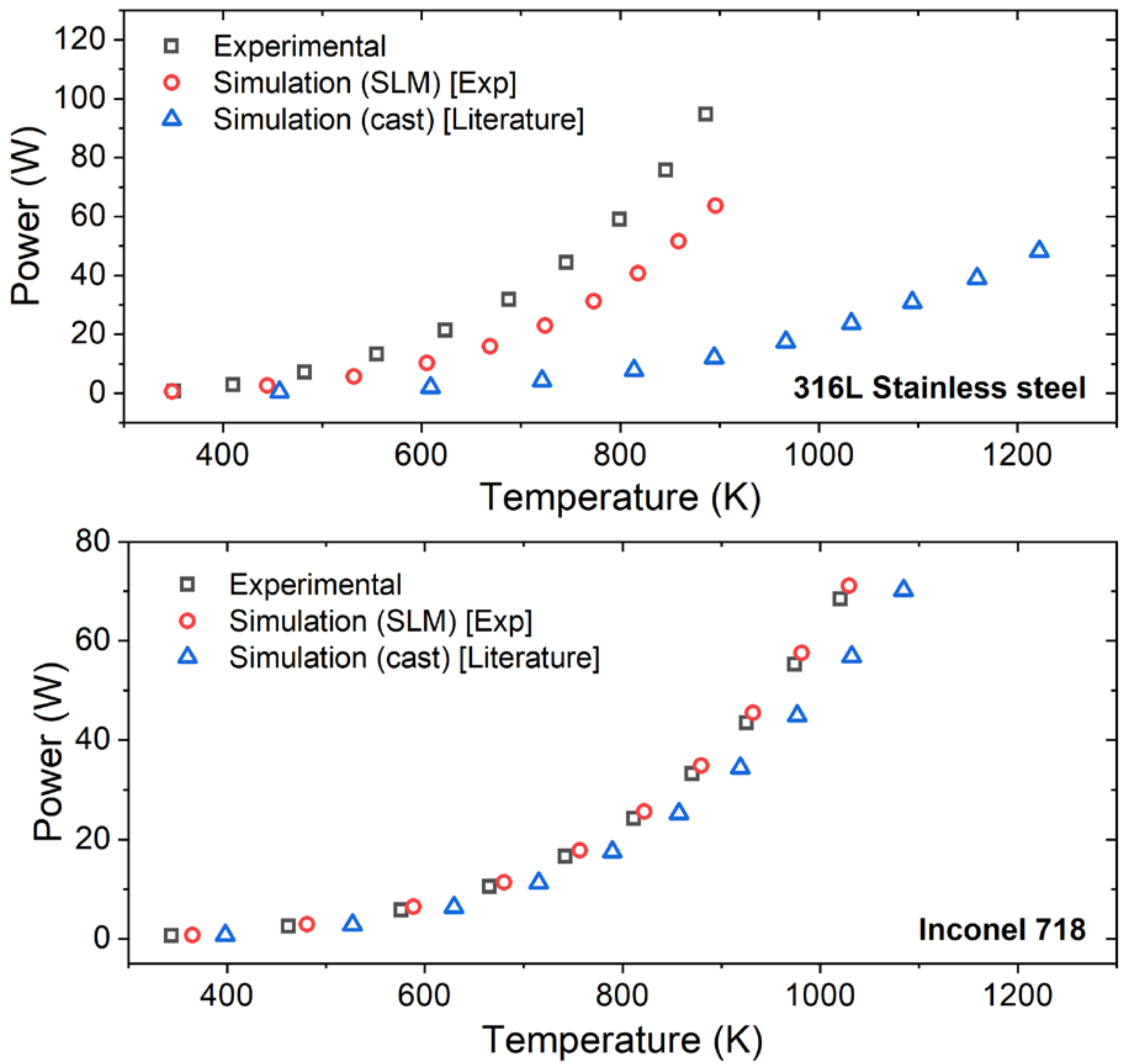
Emissivity Results – Additive vs. Traditional

- Emissivity increases with roughness
- Additive parts show higher emissivity than cast parts
- 316L Stainless Steel
  - Sample oxidised during testing
- Inconel 718
  - Decrease in emissivity at low temperatures due to experimental error



Results – Simulation vs Experimental

- Simulations using literature values deviate significantly from experimental values
- Simulations using experimentally determined material properties more closely match experimental values
  - 316L shows significant deviation power at high temperature



Conclusions

- Emissivity and Resistivity of as-received SLM parts notable higher than literature values for cast materials
- Simulation results for Inconel 718 show good agreement with experimental data
  - Shows better agreement with experimental than COMSOL values
  - Resistivity of 316L shows good agreement, however temperature difference needs investigation

Next Steps

- Apply data to full simulation of the resistojet
- Obtain Emissivity and Resistivity data for more materials
- Improve Simulation results
  - Obtain better cross section areas
    - Improve surface determination in CT scans
  - Refine mesh used in simulations
- Investigate influence of SLM process parameters on surface quality
  - Roughness
  - Microstructure

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Thank you for listening!
Any Questions?

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Additional publications:

- M. Robinson, A. Grubišić, G. Rempelos, F .Romei, C .Ogunlesi, and S .Ahmed, , “Endurance testing of the additively manufactured STAR resistojet,” Materials & Design, vol 180, article 107907, 2019

- F. Romei, A. N. Grubisic, and D. Gibbon, “High performance resistojet thruster: STAR Status Update,” in Space Propulsion 2018, 2018.

- F. Romei, A. N. Grubišić, and D. Gibbon, “Manufacturing of a high-temperature resistojet heat exchanger by selective laser melting,” Acta Astronaut., vol. 138, pp. 356–368, 2017.