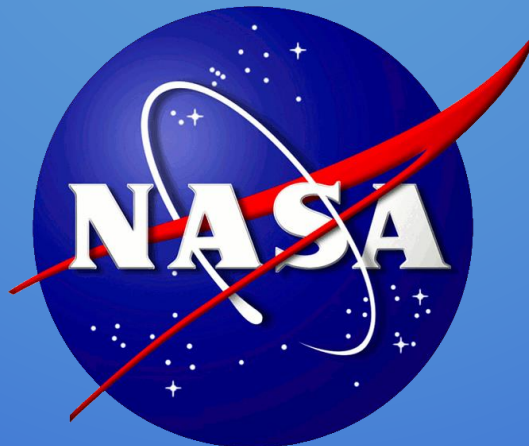


# Thermal, Fluid, Mechanical, and Microstructural Property Characterization of Additively Manufactured Lattice Structures

Omar Mireles, Carlos Gomez, William Tilson, Travis Belcher, Brandon Abranovic,  
Mariana Chaidez, John Lopez, Christopher Romanowski, and Lief Wesche.

NASA Marshall Space Flight Center



Approved for public release; distribution is unlimited.

# Lattice Structure Applications

- Applications

- Reduce weight, retain stiffness.
- Variable relative density (%RD) & surface area.
- Permeable solid: metal porous foam & Regimesh replacement.
- Metal matrix composite (back infiltration).
- Custom property potential: mimic properties of different materials in the same part using the same material in adjacent regions.

- Limitations

- Computationally expensive.
- Inadequate property data.



Green Propulsion  
Thruster Catalyst Bed



Propellant Management  
Device Demo



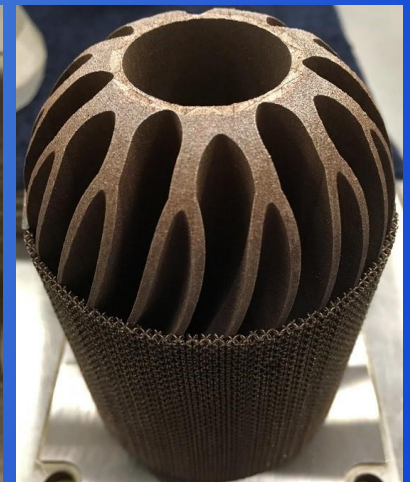
Lattice Regen  
Chamber Demo



ECLSS 4-Bed Molecular Sieve  
(4BMS-X) Heater Plate



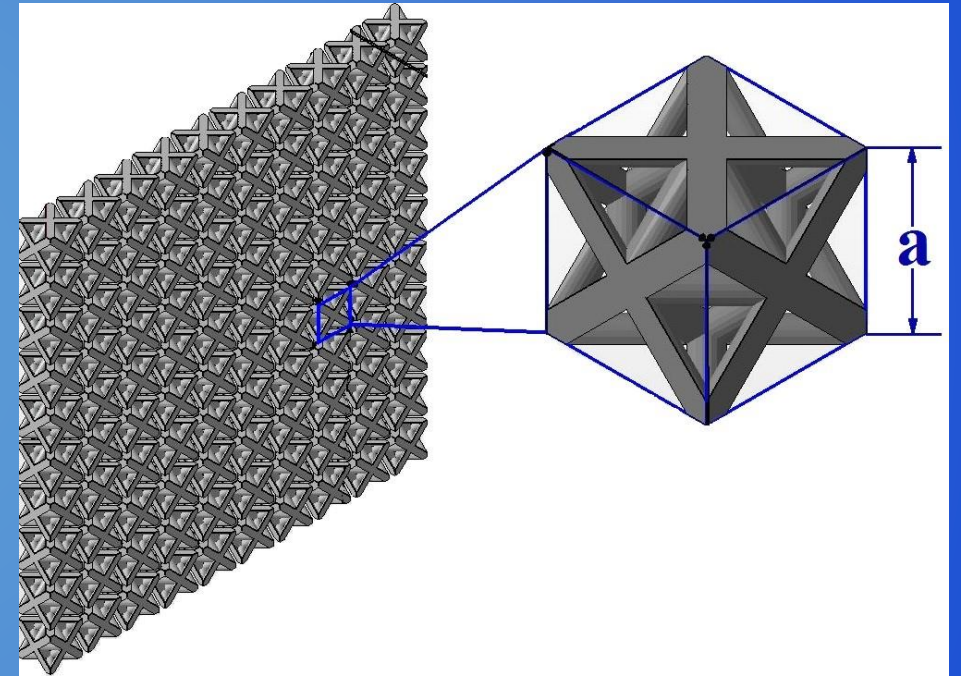
Cryo Heat Exchanger-Injector-Condenser Demonstrator



KSC O<sub>2</sub> Generator Cold-  
Head

# Objectives

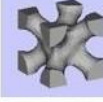




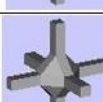



- Down-select lattice topology candidates
  - Evaluate computational expense
  - Evaluate SLM printability
- Investigate lattice structure engineering utility
  - Mechanical properties
  - Thermal properties
  - Flow properties
  - Microstructural characterization
- Evaluate for broad-scale performance trends
  - Topology
  - Unit cell ( $a$ ) and strut thickness ( $t$ )
  - Material
  - Machine



Lattice unit cell ( $a$ ) and strut thickness ( $t$ ).

# Computational Expense

- Lattices topology generation
  - Materialise Magics structures module
- Standardized volume
  - 10x10x10 mm cube
- Unit Cell Sizes
  - 1 mm & 10 mm
  - Strut dependent on unit cell
- Established selection criteria
  - Processing time
  - File size
  - SLM printability

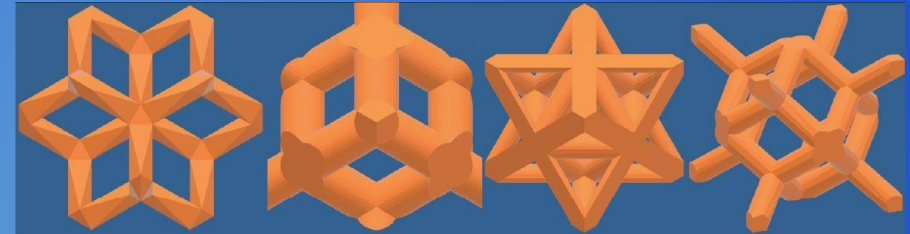
| No | Name                                | Image   | Unit Cell (mm) | Processing Time (s) | .stl Size (KB) | Used in Test Builds?     | Successful Build?              | Machine  |
|----|-------------------------------------|---|----------------|---------------------|----------------|--------------------------|--------------------------------|----------|
| 1  | Body diagonals with nodes rounded   |    | 10             | 1                   | 144            |                          |                                |          |
|    |                                     |   | 1              | 300                 | 56021          |                          |                                |          |
| 2  | Body diagonals with nodes           |    | 10             | 1                   | 126            |                          |                                |          |
|    |                                     |   | 1              | 240                 | 15,296         |                          |                                |          |
| 3  | Cross (10.4% relative density)      |    | 10             | 1                   | 4              | ASTM E8 - 0.5 mm         | N - 90 deg unsupported surface | M290     |
|    |                                     |   | 1              | 3                   | 2442           |                          |                                |          |
| 4  | Cross-1                             |    | 10             | 1                   | 8              |                          | N - 90 deg unsupported surface |          |
|    |                                     |   | 1              | 4                   | 6350           |                          |                                |          |
| 5  | Cross-2                             |    | 10             | 1                   | 6              |                          | N - 90 deg unsupported surface |          |
|    |                                     |   | 1              | 3                   | 4788           |                          |                                |          |
| 6  | Cross-3                             |    | 10             | 1                   | 6              |                          | N - 90 deg unsupported surface |          |
|    |                                     |   | 1              | 3                   | 4006           |                          |                                |          |
| 7  | Cross-X                             |   | 10             | 1                   | 22             |                          |                                |          |
|    |                                     |   | 1              | 35                  | 6131           |                          |                                |          |
| 8  | Cross-X reinforced                  |  | 10             | 1                   | 5              |                          | N - 90 deg unsupported surface |          |
|    |                                     |   | 1              | 3                   | 1911           |                          |                                |          |
| 9  | Diamond 20 percent relative density |  | 10             | 5                   | 384            | Lattice Backfill 2, 4 mm | Y - All                        | M1, M290 |
|    |                                     |   | 1              | 600                 | 19331          |                          |                                |          |

Example of lattice generation time and file size.

# Metal Printability

- Down-Selected 4 lattice cell topologies

- Diamond - 20%RD
- Dode Medium - 13%RD
- Octet Truss - 30%RD
- Rhombic Dodecahedron - 20%RD



Dode Medium-  
13%RD

Diamond-  
20%RD

Octet Truss  
-30%RD

Rhombic  
Dodecahedron  
-20%RD

- Down-Selected 2 lattice unit cell sizes

- Course: 5 mm
- Fine: 2 mm

- Specimens produced on several platforms

- EOS M290: IN718, stress relief, HIP, and solution/age per AMS 5664.
- Concept Laser M1: IN625, annealed.
- Concept Laser M2: GRCop84, as built.
- Concept Laser X-Line 1000R: AlSi10Mg, as built at stress relief temp.



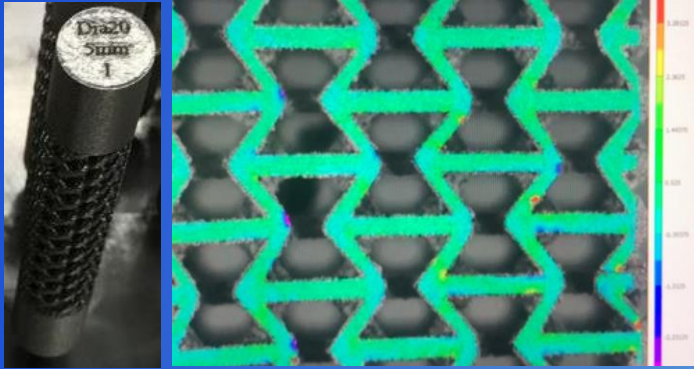
GRCop84 Met Cubes.  
(L) a = 5 mm, (R) = 2 mm.

- Cross-Sectional Area Measurement

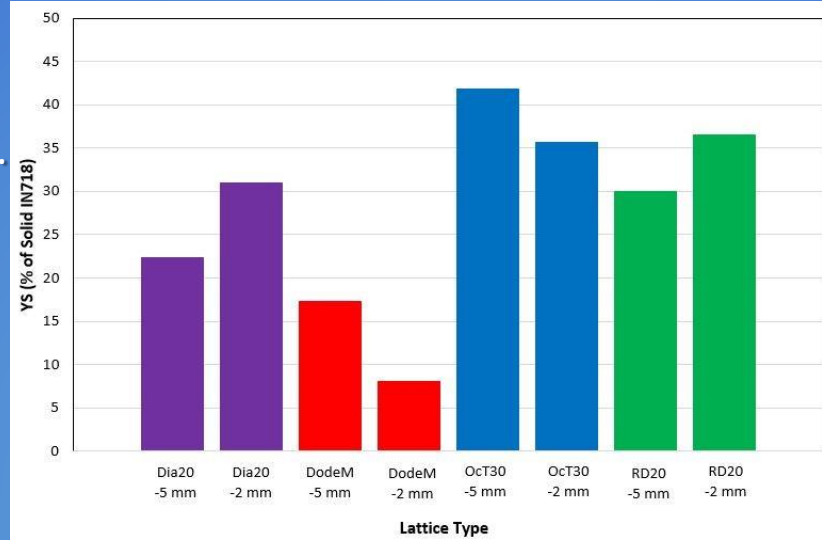
- CAD
- Specimen

# Mechanical Testing

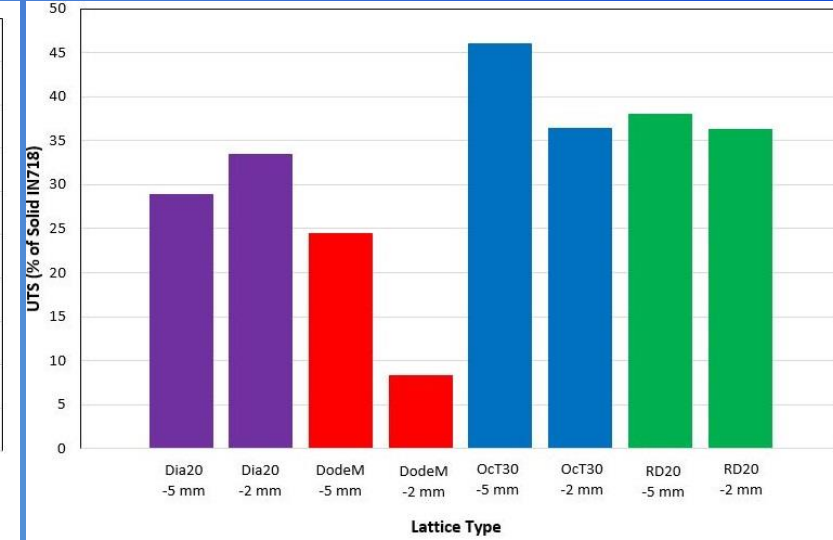
- IN718 – fully heat treated
- Strength calculations based on assumed minimum cross sectional area from CAD.
- Displacement control rate: 0.508 mm/min.



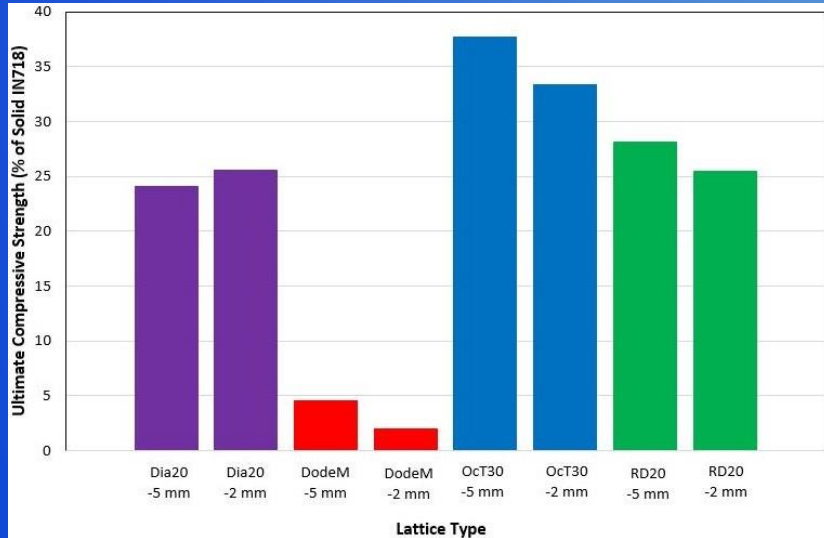
Lattice Compression Strain Field



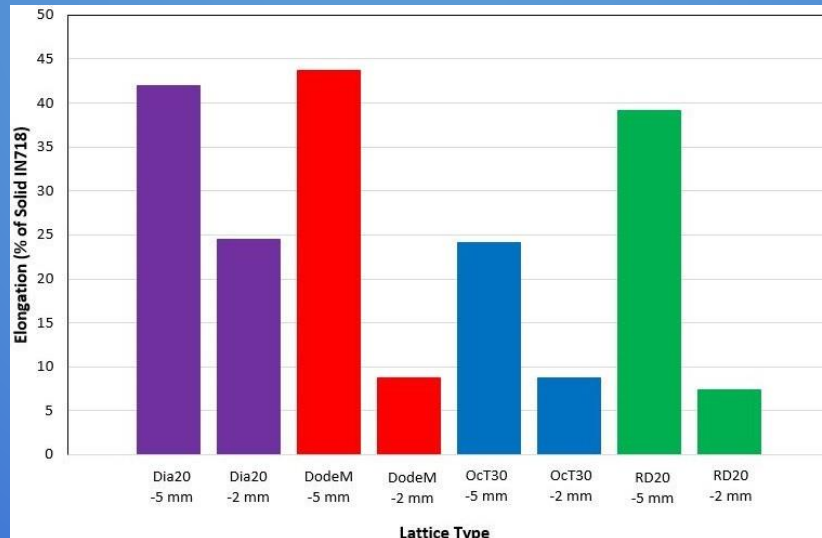
Effective Yield Strength of IN718 Lattice



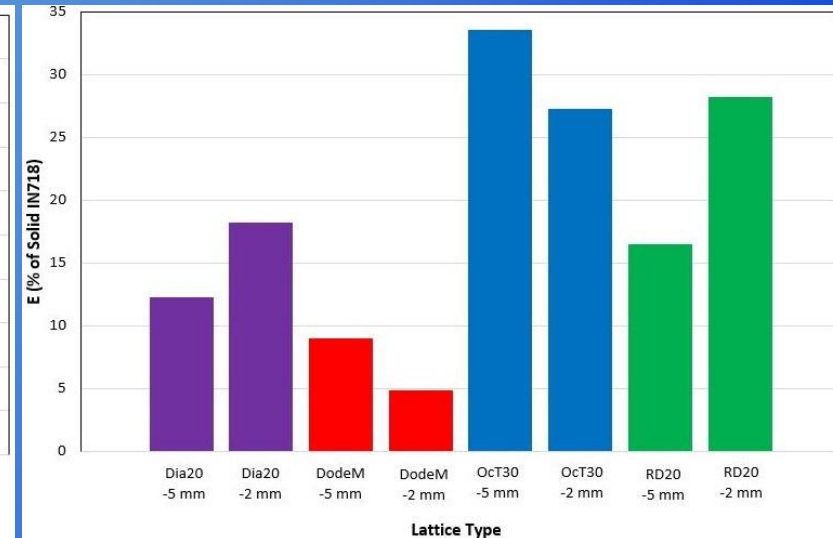
Effective Ultimate Strength of IN718 Lattice



Effective Ultimate Compressive Strength of IN718 Lattice

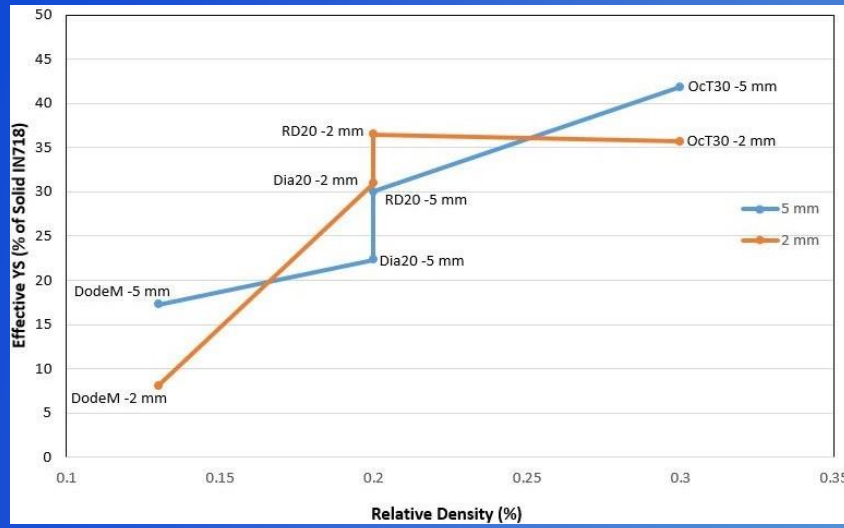


Effective Elongation of IN718 Lattice

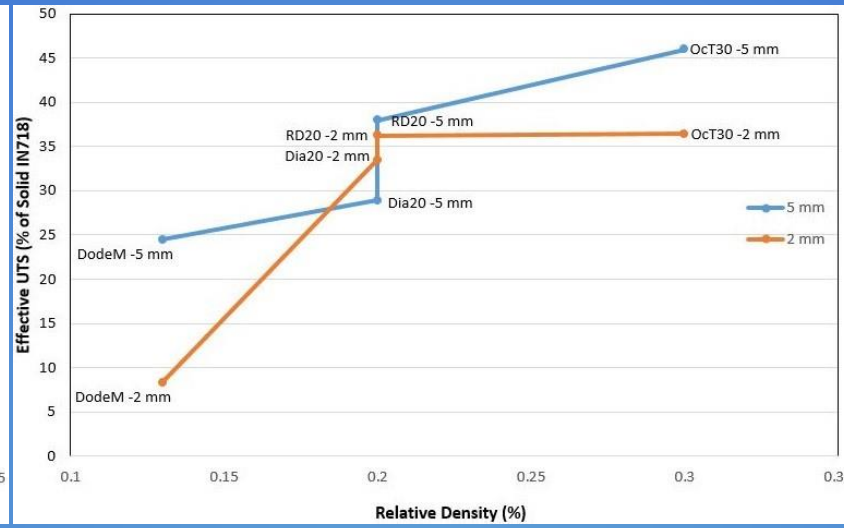


Effective Modulus of IN718 Lattice

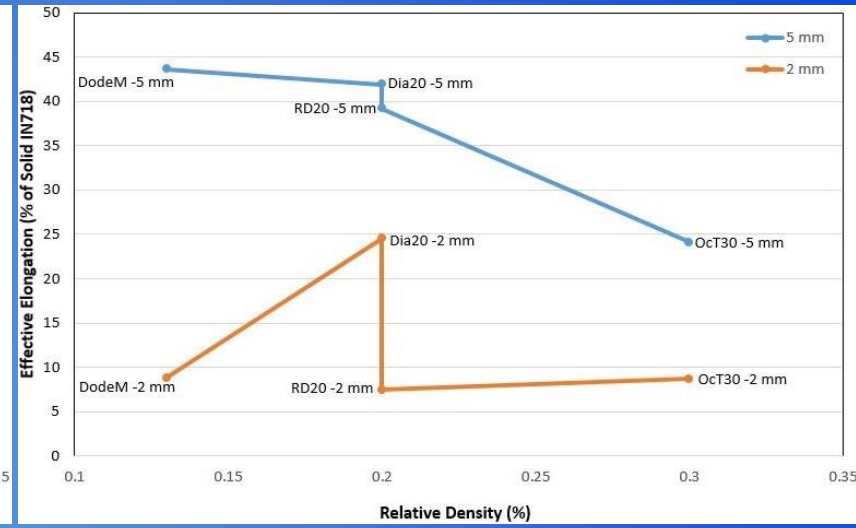
# Mechanical Testing



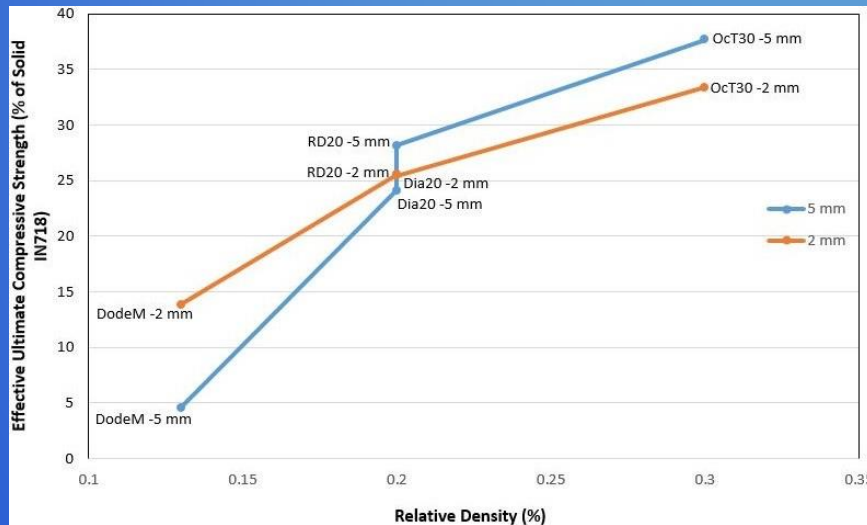
Effective Yield Strength vs. %RD



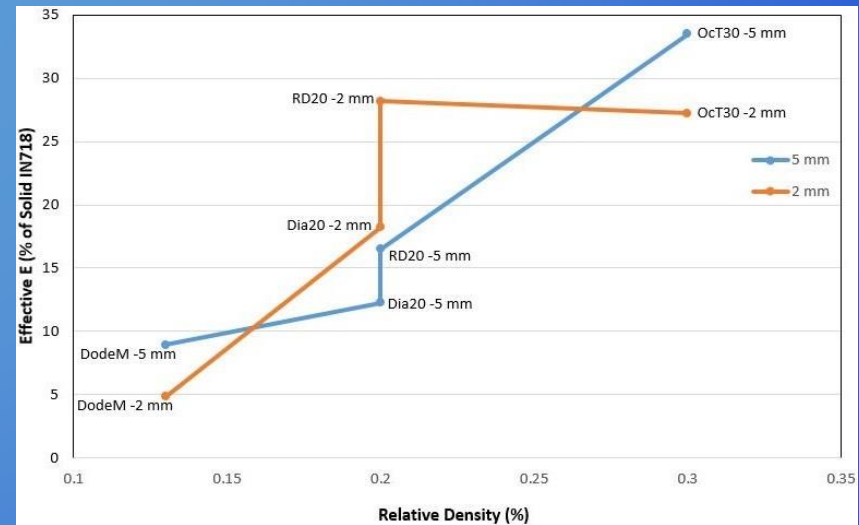
Effective Ultimate Strength vs. %RD



Effective Elongation vs. %RD



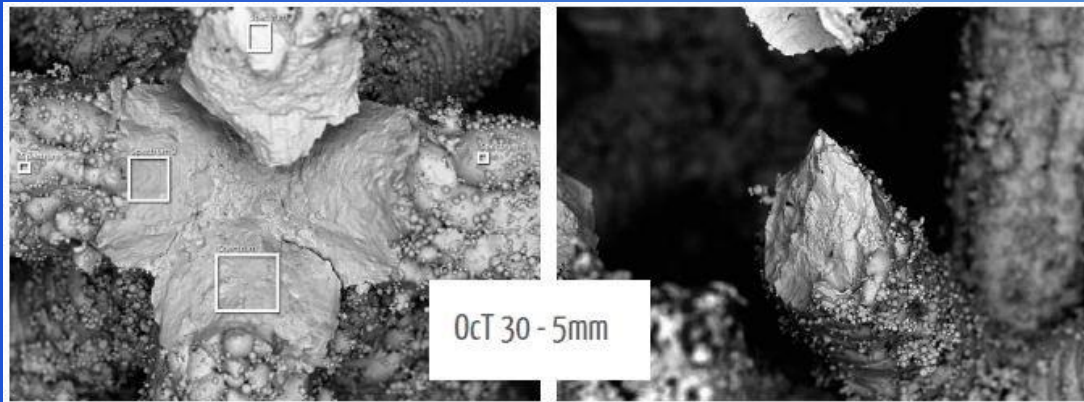
Effective Ultimate Compressive Strength vs. %RD



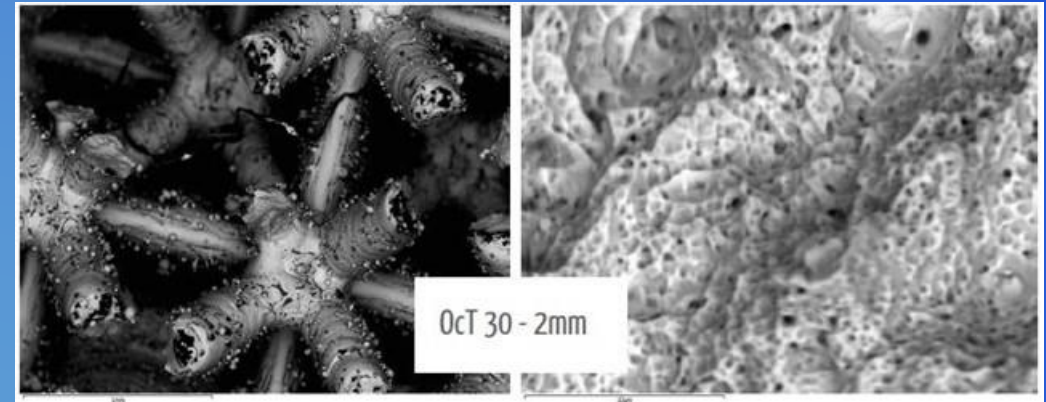
Effective Modulus vs. %RD

- Strong dependence on %TD followed by lattice topology and to a lesser extent unit cell size.

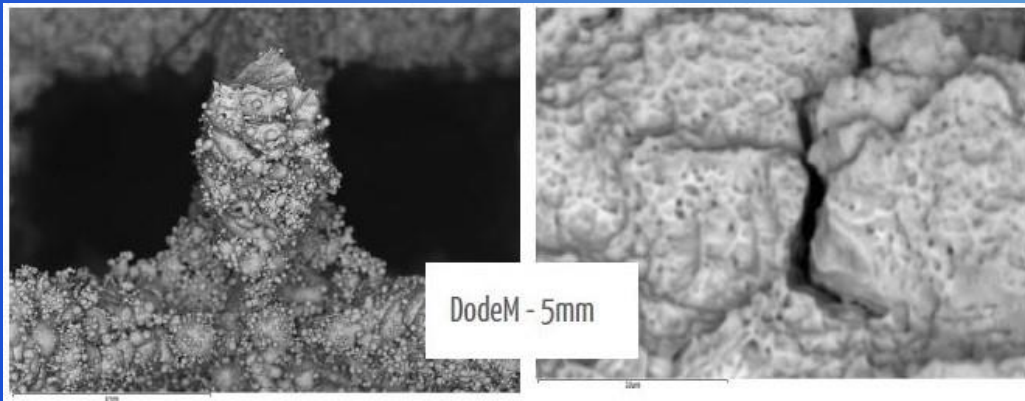
# Fracture Surface Inspection



Fractures consistently occur at similar points within a unit cell.



Dimple ductile fracture.



Prone to crack nucleation and low strain failure.



Ductile and brittle signatures at different regions on fracture.

# Model Control Volume & Boundary Conditions

- Steady State.
- Aluminum properties assumed constant with temperature to simplify effective thermal conductivity calculations.
  - $K = 205 \text{ W/m-K}$
  - $C_p = 0.9 \text{ J/g-K}$
  - $\rho = 2700 \text{ kg/m}^3$

$$k = \frac{QL}{A\Delta T}$$

$k$  - Thermal Conductivity

$Q$  - Heat Flux

$L$  - Length

$A$  - Cross-Sectional Area

$\Delta T$  - Differential Temperature

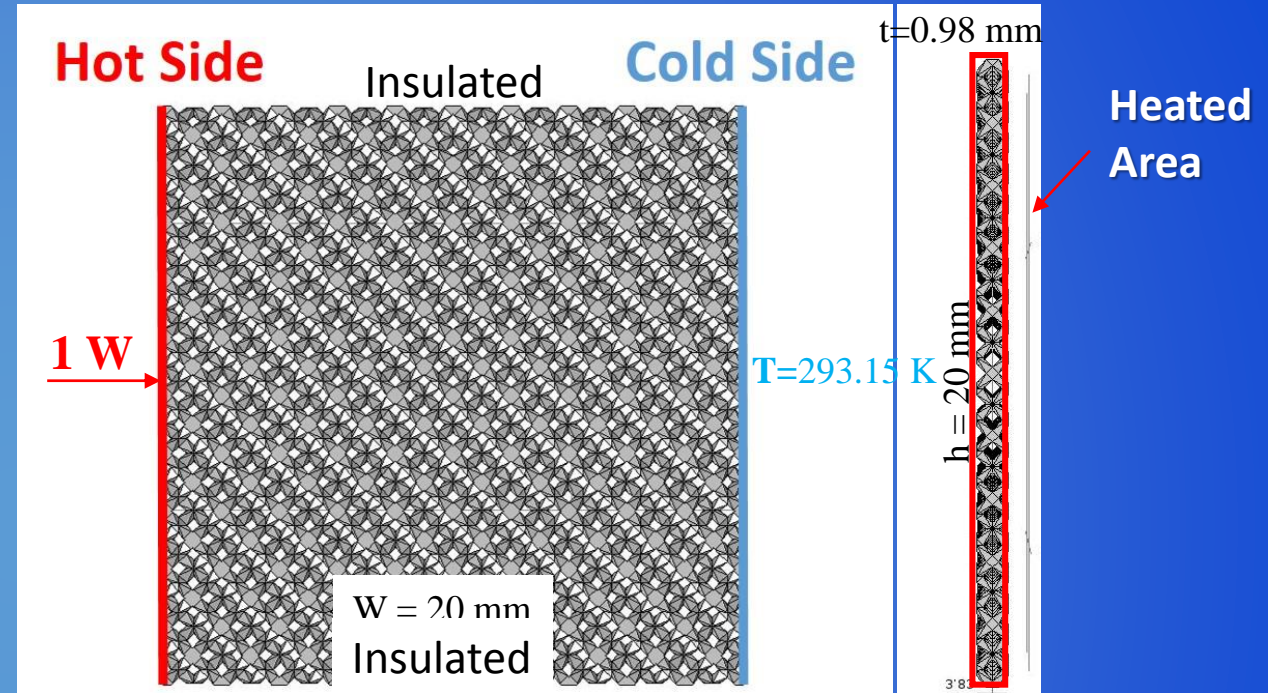
$$\alpha = \frac{k_{eff}}{\rho_{eff}C_p}$$

$\alpha$  - Thermal Diffusivity

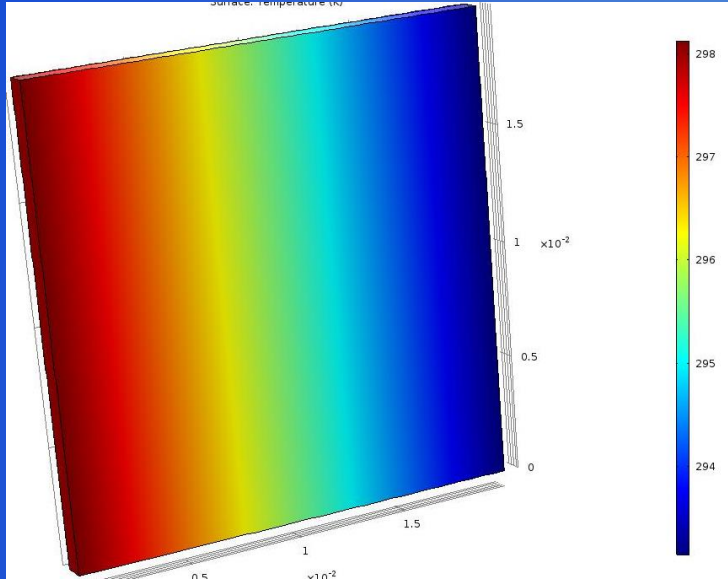
$k_{eff}$  - Effective Thermal Conductivity

$\rho_{eff}$  - Effective Density ( $M_{model}/V_{max}$ )

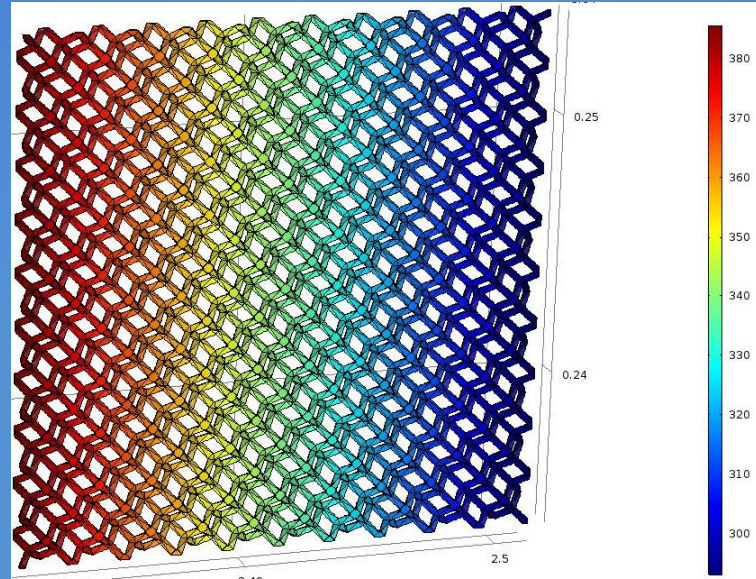
$C_p$  - Specific Heat Capacity



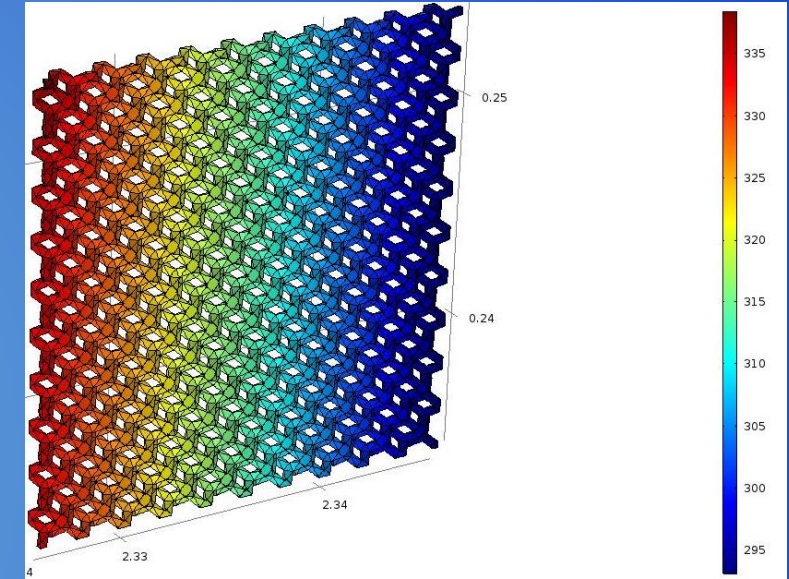
# Simulation Results



Solid Model



Medium Lattice Model



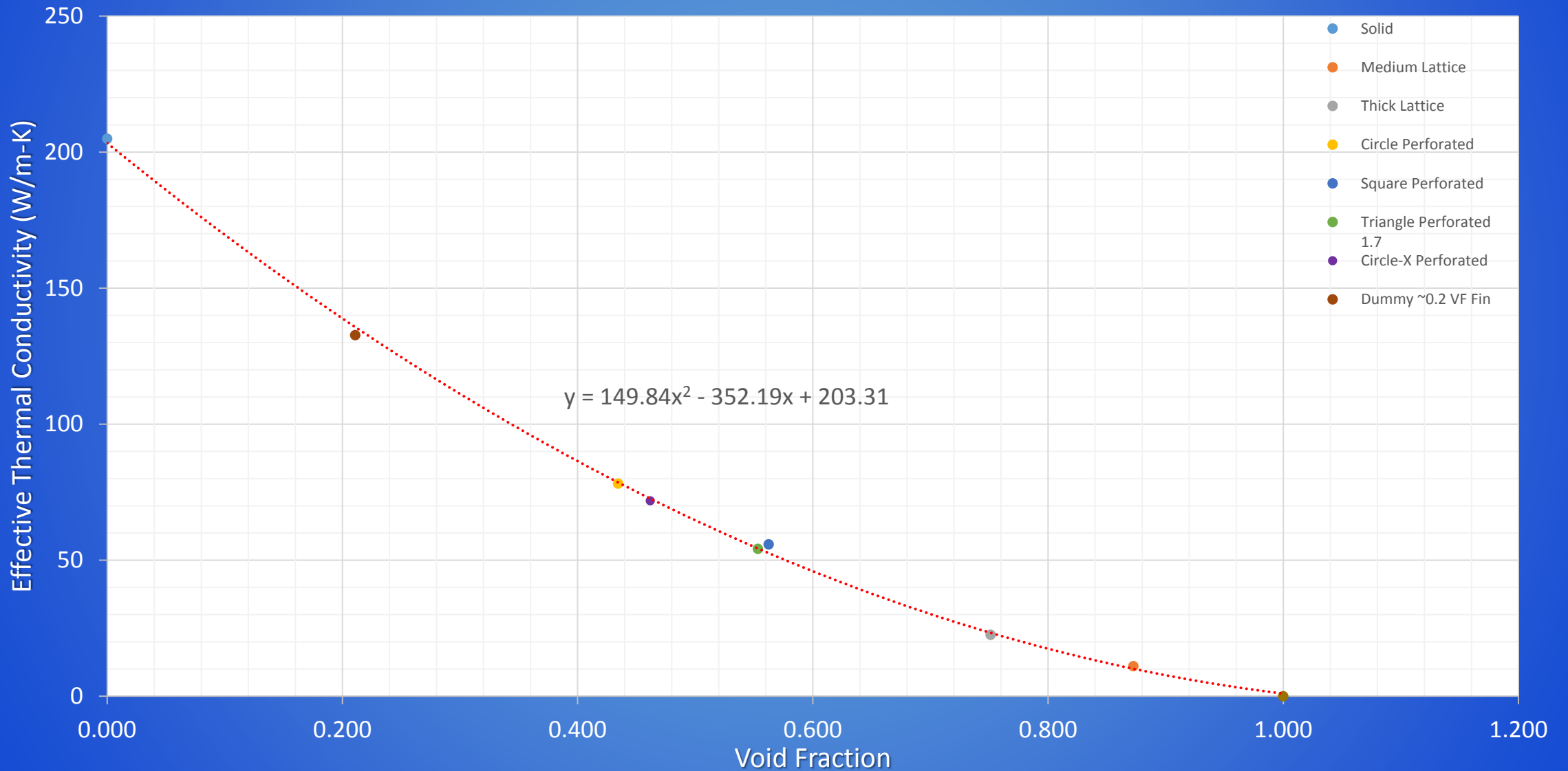
Thick Lattice Model

| Model          | Surf. Area (mm <sup>2</sup> ) | Volume (mm <sup>3</sup> ) | Mass (g) | $\Delta T$ (K) | $k_{\text{eff}}$ (W/m-K) | $\alpha$ (mm <sup>2</sup> /s) | Void Fraction |
|----------------|-------------------------------|---------------------------|----------|----------------|--------------------------|-------------------------------|---------------|
| Solid          | 878.4                         | 392.0                     | 1.058    | 4.98           | 204.9                    | 84.32                         | 0.000         |
| Medium Lattice | 933.6                         | 49.96                     | 0.135    | 92.45          | 11.04                    | 35.64                         | 0.873         |
| Thick Lattice  | 1240                          | 97.54                     | 0.263    | 45.27          | 22.54                    | 37.28                         | 0.751         |

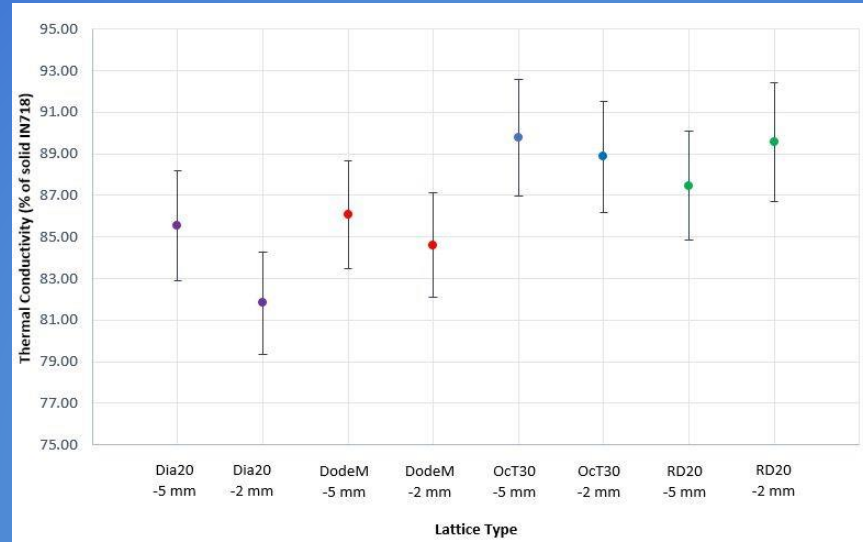
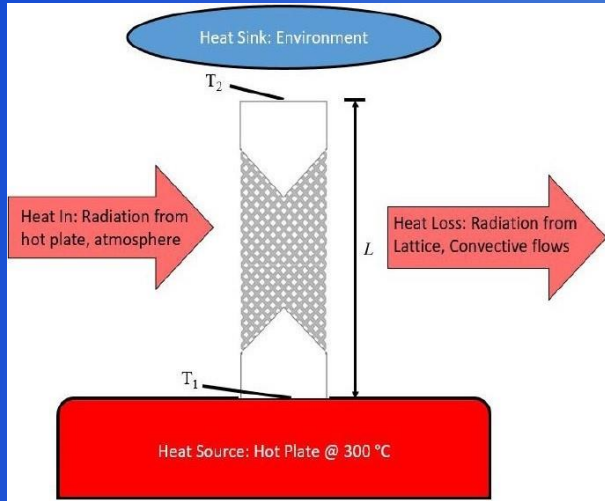
$$\text{Void Fraction} = 1 - \rho_{\text{rel}}$$

# Effective Thermal Conductivity vs. Void Fraction

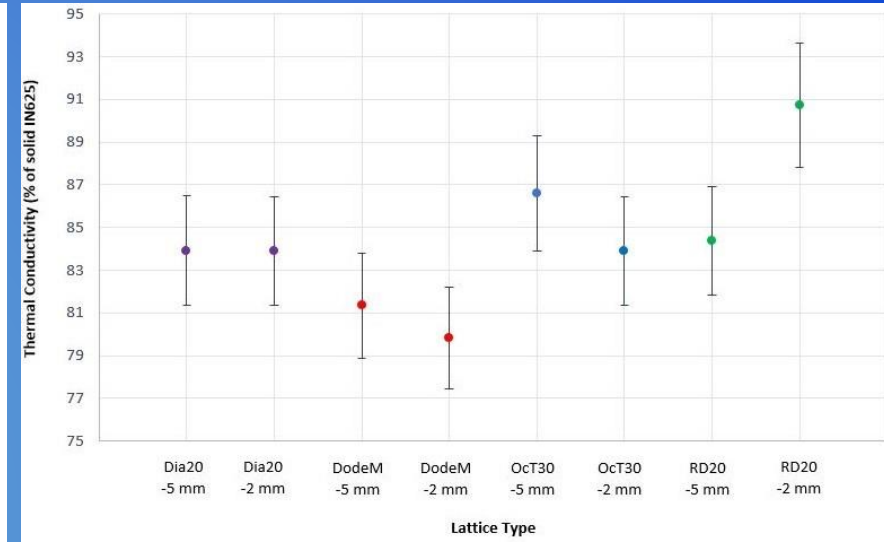
- Effective thermal conductivity is inversely proportional to void fraction, which is lattice geometry specific.



# Thermal Conductivity



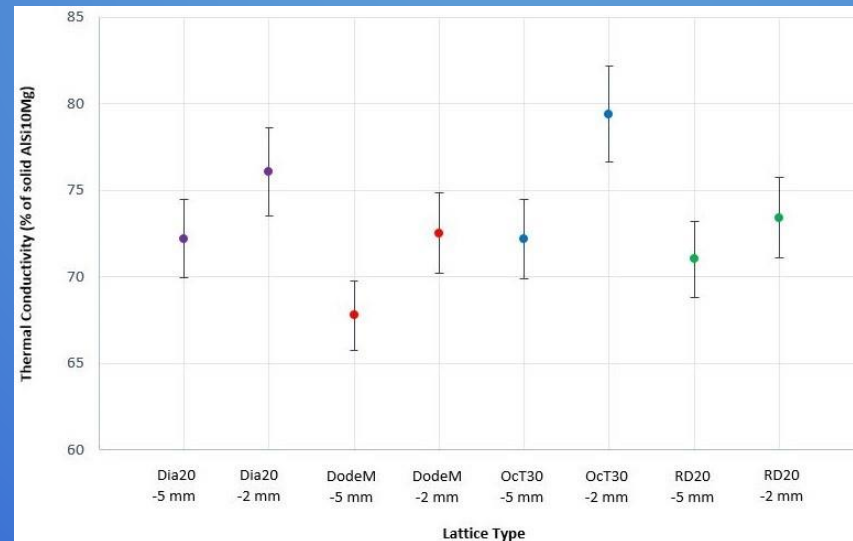
Thermal conductivity of IN718 lattices.



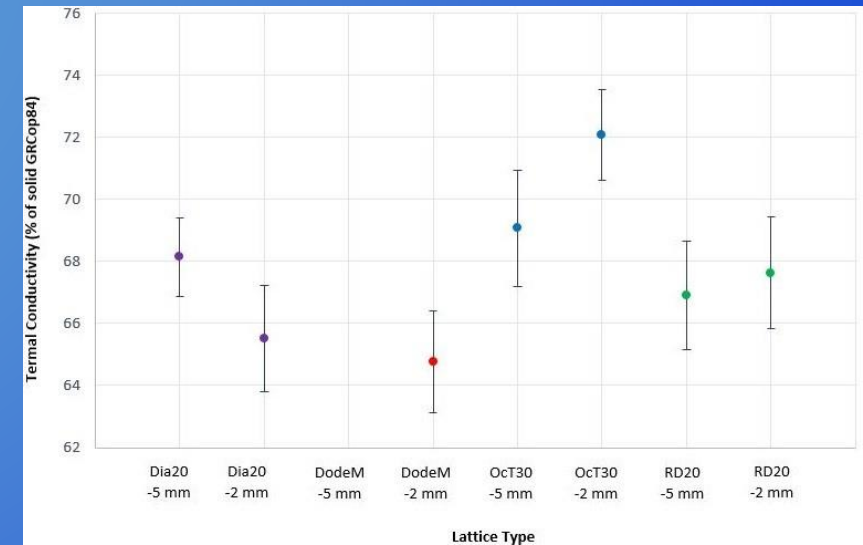
Thermal conductivity of IN625 lattices.



Thermal conductivity specimen and experimental test apparatus based on modified ASTM 1225-04.



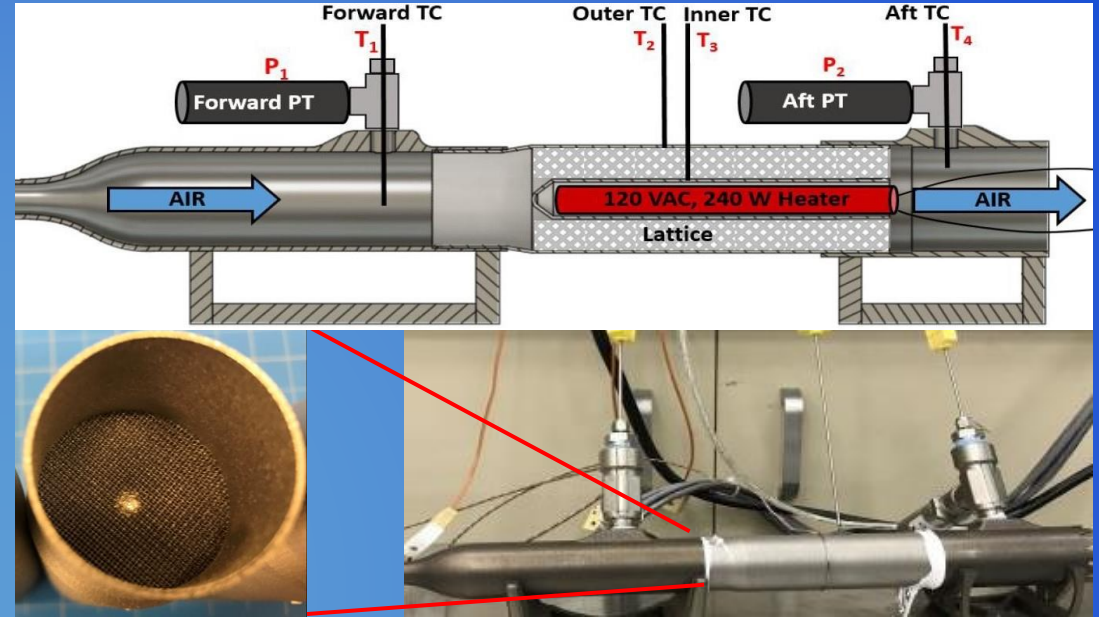
Thermal conductivity of AlSi10Mg lattices.



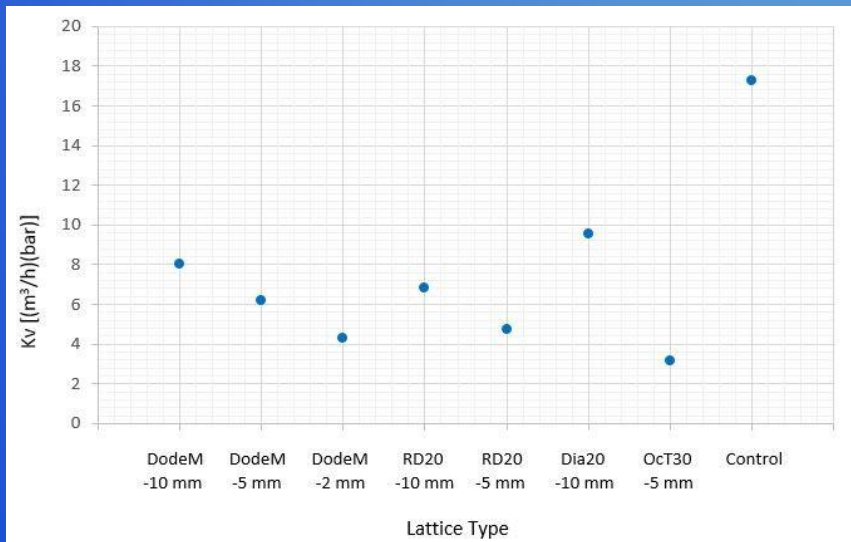
Thermal conductivity of GRCo84 lattices.

# Flow & Convective Heat Transfer Coefficients

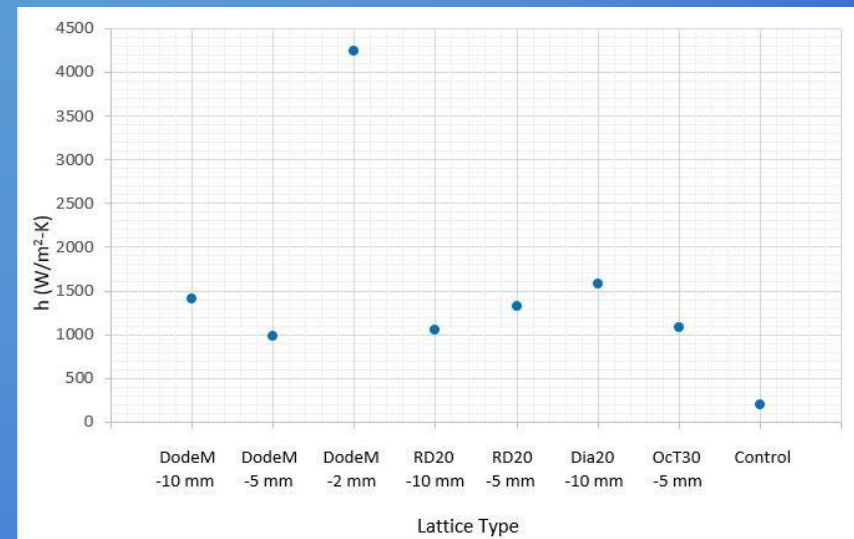
- Flow Coefficient ( $K_v$ )
  - Flow rate ( $\text{m}^3/\text{hr}$ ) of water at  $16^\circ\text{C}$  with a pressure drop across a valve of 1 bar.
  - $C_v = 1156 \cdot K_v$
- Convective Heat Transfer Coefficient ( $h$ )
  - Packed bed model
  - Order of magnitude difference between predicted and experimental results.



Annulus specimen & test apparatus.



Flow coefficients of lattice types.



Convective heat transfer coefficient of lattice types.

# Lattice Infiltration

- Low cost metal matrix composite (MMC)
  - High strength structure.
  - High thermal conductivity infill.
  - Functional transition gradient.
- IN718 lattice cube (10x10x10 mm) in mold cup
  - Specimens printed on the M290.
  - Vibratory fill with C18150 power.
- Infiltration
  - 1093 °C for 1 hr in argon to melt C18150.
- Infiltration Evaluation
  - Metallographic preparation.
  - Imaged using Canon EOS T6 camera and Keyence VHX-500 optical microscope at 100x.

| Material         | $\rho$ (g/cm <sup>3</sup> ) | T <sub>m</sub> (°C) | k (W/m-K) | Notes                 |
|------------------|-----------------------------|---------------------|-----------|-----------------------|
| IN718            | 8.22                        | 1370-1430           | 6.5       | AM cup & lattice cube |
| C18150 (CuCr1Zr) | 8.89                        | 1080                | 323.4     | Backfill powder       |

| Sample Number | Lattice Style                             | Unit Cell (mm) |
|---------------|---|----------------|
| 1             | Dode-Medium (13% relative density)        | 5.0            |
| 2             |   | 2.0            |
| 3             | Rhombic Dodecahedron-20% relative density | 5.0            |
| 4             |   | 2.0            |
| 5             | Diamond-20% relative density              | 5.0            |
| 6             |   | 2.0            |
| 7             | Octet Truss-30% relative density          | 5.0            |
| 8             |   | 2.0            |
| 9             | Cross - 10.4% relative density            | 2              |

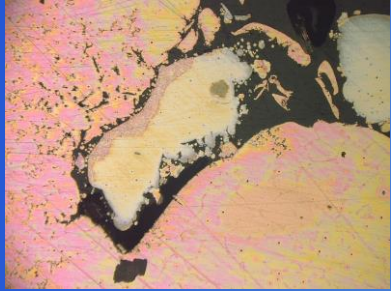


Back Infiltration Specimen Build

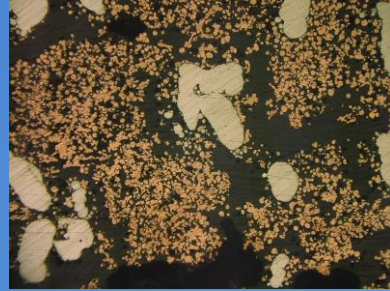


Vibratory Powder Fill Station

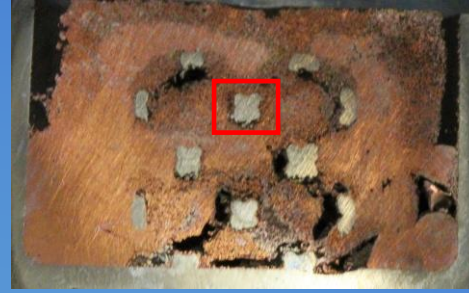
# Infiltration Results



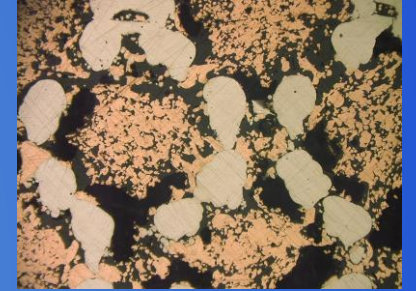
Dode M - 13%RD - 5 mm



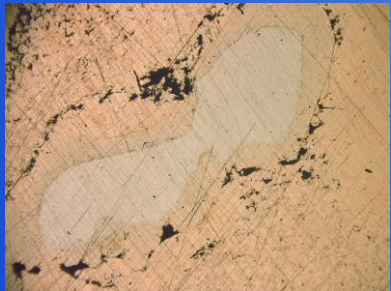
Dode M - 13%RD - 2 mm



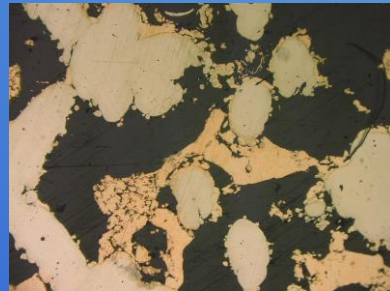
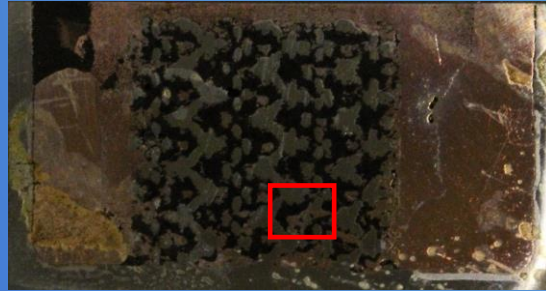
Rhombic Dodecahedron - 20%RD - 5 mm



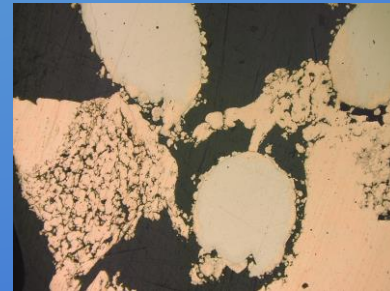
Rhombic Dodecahedron - 20%RD - 2 mm



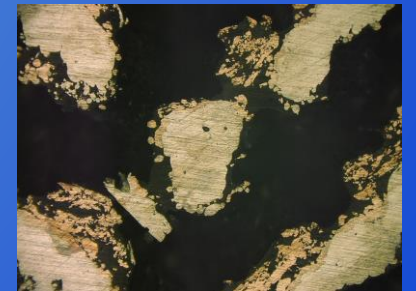
Diamond - 20%RD - 5 mm



Diamond - 20%RD - 2 mm



Octet Truss - 30%RD - 5 mm



Octet Truss - 30%RD - 2 mm

# Conclusions

- Mechanical properties primarily influenced %RD, secondarily by lattice topology, and finally by unit cell size.
- Coarse unit cell structures exhibit significantly greater elongation before failure compared to fine unit cells due to thicker strut sizes.
- Thermal conductivity proportional to %RD and not necessarily to lattice topology or unit cell size.
- Flow coefficient proportional to unit cell size: fine unit cells have more struts per unit volume and therefore higher flow losses.
- Convective heat transfer coefficient inversely proportional to unit cell size: fine unit cells have more surface area per unit volume.
- Infiltration density proportional with unit cell size and topology open cell volume.

# Recommendations for Future Work

- Functional gradient and topology optimized structures generated with Autodesk Netfabb.
- Repeat characterization on optimized topologies.
- Independent evaluation of topologies with FEA tools.
- Compare mechanical test to simulation predictions.
- Centrifugal casting or HIP to aid in near-fully dense infiltration.
- Ultra-fine lattice structure with customized parameters.

# Acknowledgments

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- The opinions expressed in this presentation are those of the author and do not necessarily reflect the views of NASA or any NASA Project.

