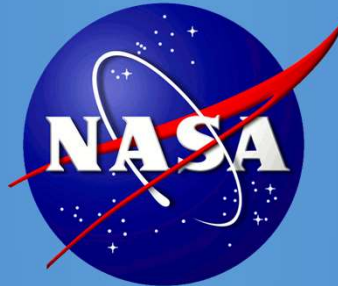


Additive Manufacture of Ultra-Fine Lattice Structures of Green Propulsion Catalyst

Omar Mireles, Zack Jones, Omar Rodriguez.
NASA Marshall Space Flight Center

Maryna Ienina
EOS North America



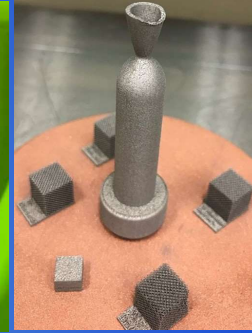


Background

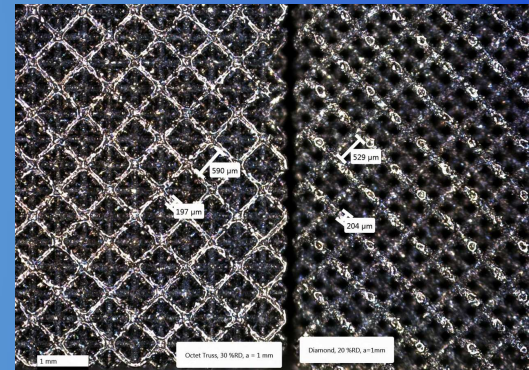
- Metal or ceramic foams used for propulsion catalysts, evaporative heat exchangers, insulators, etc.
- Foams exhibit anisotropic properties and can be expensive.
- Ultra-fine lattice structures are repeating unit cells with very thin strut thickness produced through additive manufacture (AM) with high spatial symmetry and tailorable properties.
- Objectives
 - Investigate viability to replace foams with AM lattice structures.
 - Improve property repeatability and reduce cost/schedule.
- Tasks
 - Identify desired lattice designs (MSFC).
 - Parameter development: TiAl64V & W (EOS).
 - Metallography (MSFC).
 - μ -CT (3D Engineering Solutions).
 - Compressive strength (MSFC).
 - ΔP characterization (UTEP).



EOS M100 printing W lattice specimens.



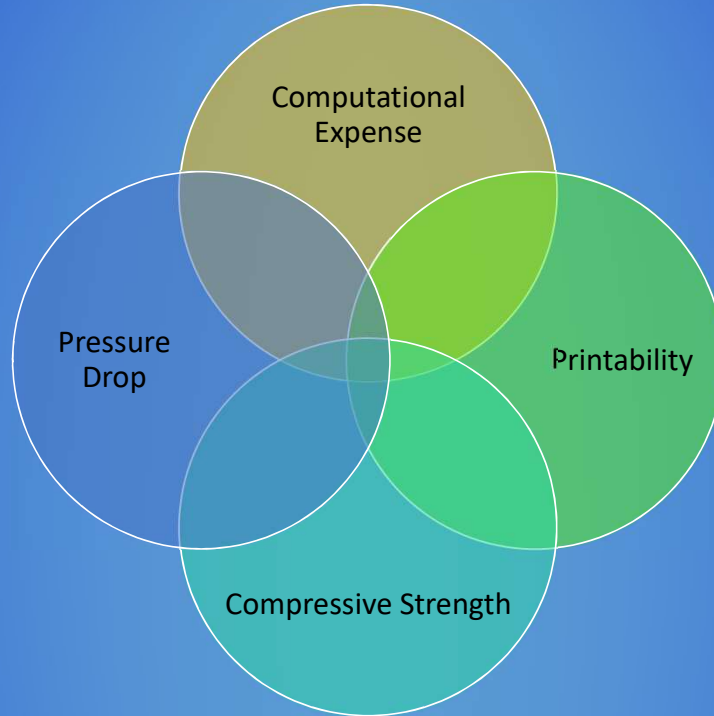
W nozzle & lattices.



Optical micrograph of Octet Truss (30 %RD) and Diamond (20 %RD) lattice specimens with 1 mm unit cells printed from W at 100x.



Selection Criteria

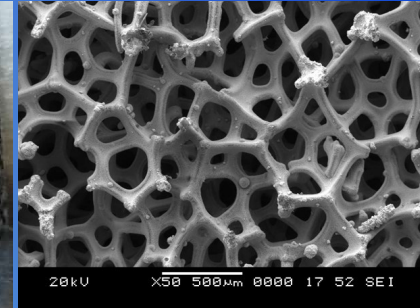


Lattice Design

- Traditional catalyst manufacture: graphite or ceramic foam coated with a platinum group metal such as iridium.
- Foam pore size and strut thickness measured using optical and SEM micrographs to generate lattice topology and size requirements.
- Design for AM constraints used to generate lattice structure topologies that mimic foam but with greater symmetry in 3 axes.
- Existing and custom topology designed evaluated for computational expense.



Coated Foam Catalyst.

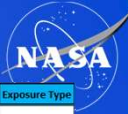


SEM micrograph of graphite foam (50x). Courtesy PPI.

Median Pore Diameter	
240 ± 153 µm	
Median Strut Thickness	
80 ± 6 µm	
Lattice Unit Cell Size Range	
343 µm	Min
707 µm	Max
400 µm	Median

Lattice structure topology requirements.

Lattice Topology Design & Build Considerations



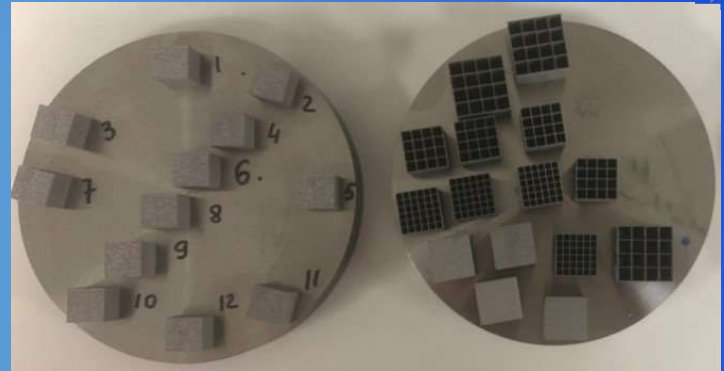
- Struts: Orient in one direction to obtain planar surface. Allows slicing as a support and to assign support exposure strategy.
- Strut & Unit Cell: Oversize slightly to offset melt pool induced geometry growth.
- Beam Offset: 0 mm. Strut diameter dependent on laser energy density and resulting melt pool diameter.
- Geometry Type: Surface, not volume. Less computational expense to render.
- Slice Type: Support. Preserve geometry, create line instead of contour laser path, allows for lower energy input.

Name	Image	Hatch lines in EOSPrint	Geometry	Exposure Type
Hexa_Profile_0m			Volume	Support
Penta_Cube_0m			Support	Support
Lattice-04_40µm_0m			Volume	Support
Lattice-04_60µm_0m			Volume	Support
Lattice-04_80µm_0m			Volume	Support
Lattice-04_70µm_surface_0m			Surface	Support
Grasshopper			Surface	Support

L-PBF Parameter Development: Ti6Al4V

- Ti6Al4V Lattice Topology Specimens

- 1-4: 70 μm Sized Surfaces
- 5: 40 μm Sized Surfaces
- 6-7: 60 μm Sized Surfaces
- 8-9: Hexa Profile
- 10-12: 80 μm Sized Surfaces
- 14-15: Penta Cube
- 16-20: Grass Hopper



Ti6Al4V print trials – DOE 1 & 2.

$$E_a = \frac{P}{vt}$$

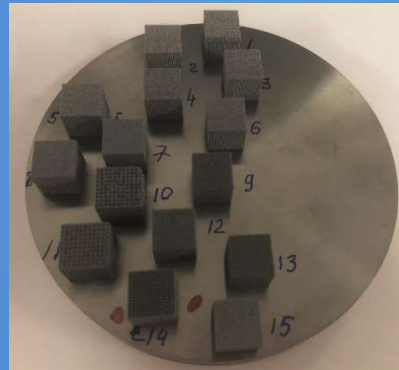
Where:

E_a = area energy density (J/mm^2)

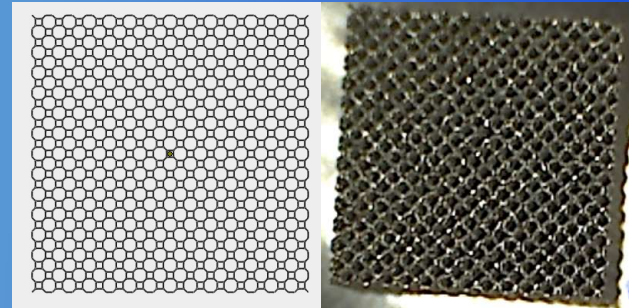
P = power (W)

v = speed (mm/s)

t = layer thickness (mm)



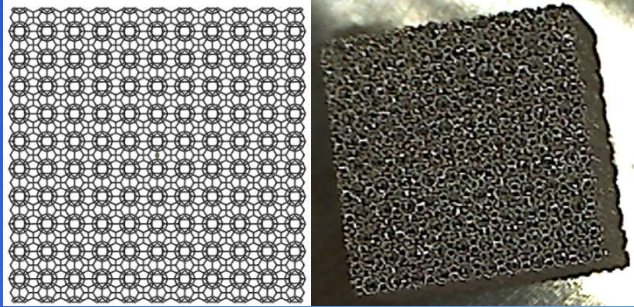
Ti6Al4V print trials – DOE 3.



Hexa Profile (XY) at 50x.



Ti6Al4V Microscopy

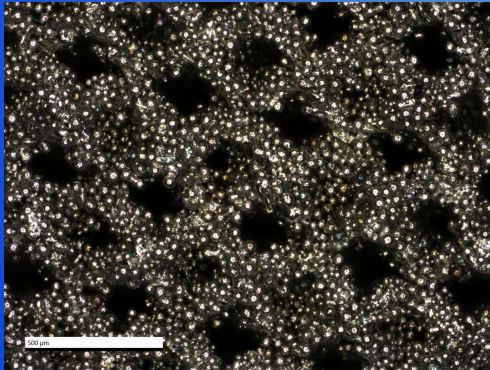


Penta Cube (XY) at 50x.

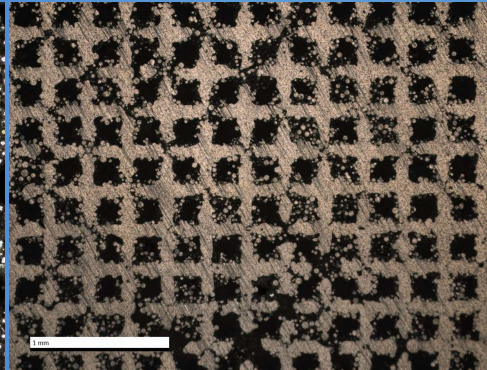
Median Pore Diameter	240 ± 153 μm	
Median Strut Thickness	80 ± 6 μm	
Lattice Unit Cell Size Range	343 μm	Min
	707 μm	Max
	400 μm	Median

Lattice structure specs.

Sample ID	Lattice Type	E_s (J/mm ²)	Cell Pore Dia (μm)	Strut Thickness (μm)	Avg Unit Cell (μm)
1	70 μm Sized Surface	2.0	169	129	313
2		1.3	153	139	
3		2.5	175	153	
4		1.7	197	137	
5	40 μm Sized Surface	2.0	187	146	329
6		1.3	185	135	
7		1.7	181	153	
8	Hexa Profile	1.7	350	165	477
9		2.0	305	133	
10	80 μm Sized Surface	1.3	181	159	363
11		2.0	250	120	
12		1.7	251	129	
13	Penta Cube	1.7	376	132	600
14		2.0	579	113	
15	Grasshopper	1.0	187	106	274
16		3.1	211	73	
17		2.0	167	90	
18		2.5	148	115	



Grasshopper (lattice 19) as-built (200x).



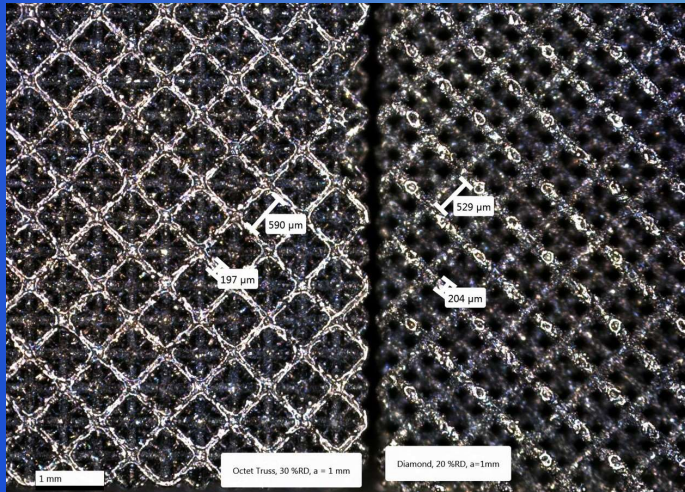
Grasshopper (lattice 16), ground surface (100x).

Ti6Al4V DOE 3 strut thickness and cell size measurements vs. E_s .

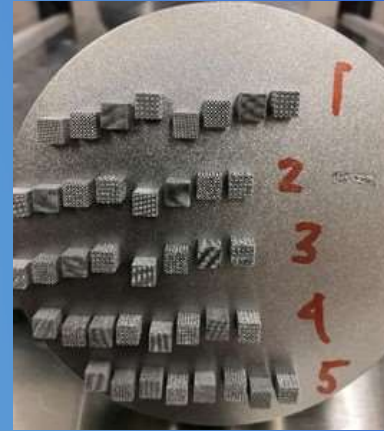
L-PBF Parameter Development: Tungsten

- W Lattice Topology Specimens

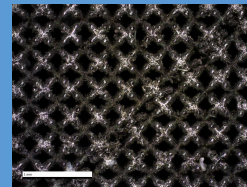
- Config 2: Hexa Profile
- Config 3: Penta Cube
- Config 4: 40 μm Sized Surfaces
- Config 5: Grass Hopper



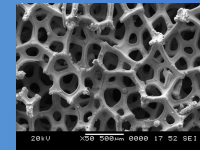
Optical micrograph of Octet Truss-30%RD (left) and Diamond-20%RD (right) W lattice specimens with 1 mm unit cells (XY, 100x).



W cube specimen print trial DOE 6

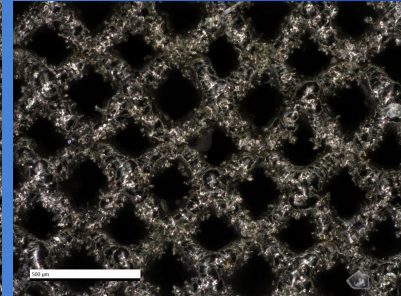
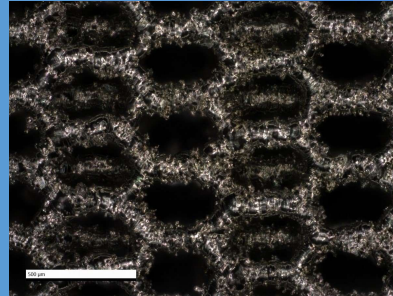
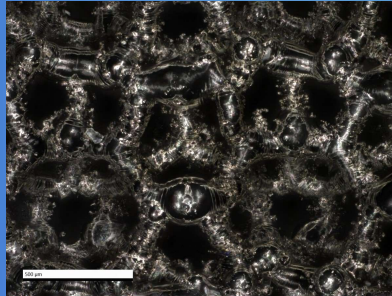
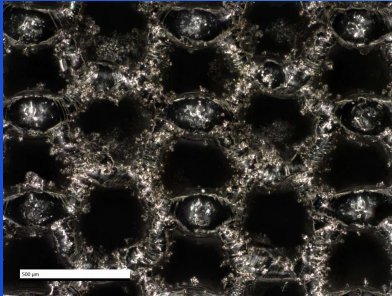
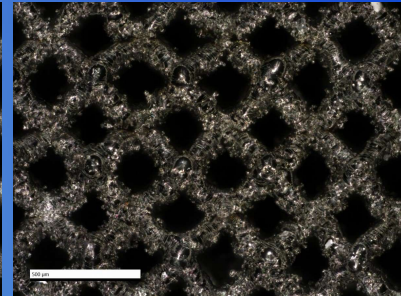
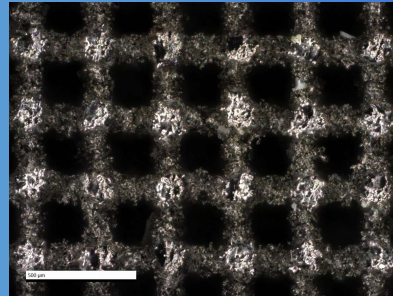
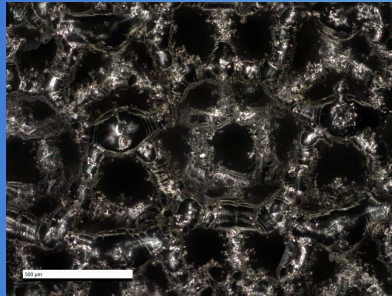
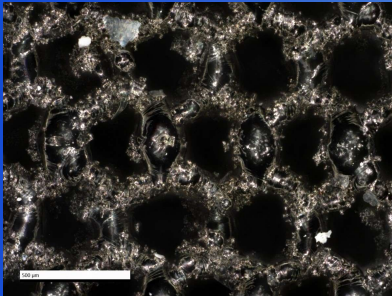


Optical micrograph of Grass Hopper W ultra-fine lattice with 274 μm unit cells (XY, 100x).



SEM micrograph of graphite foam with 400 μm median cell .

Tungsten Lattice Specimen Micrographs



Hexa W lattice, as-built in XY (top) and XZ (bottom), 200x.

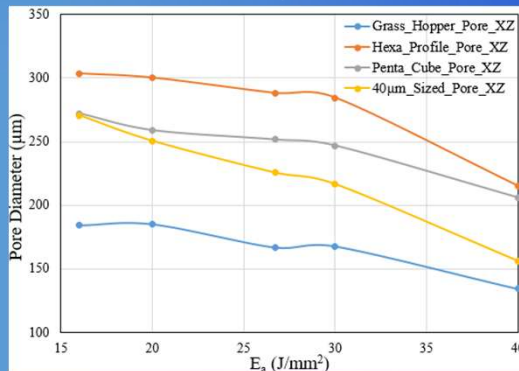
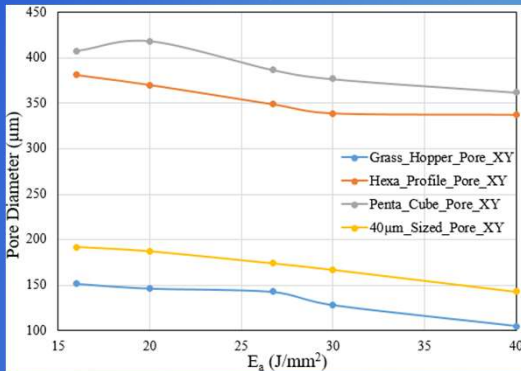
Penta Cube W lattice, as-built in XY (top) and XZ (bottom), 200x.

40 μm Sized Surface W lattice, as-built in XY (top) and XZ (bottom), 200x.

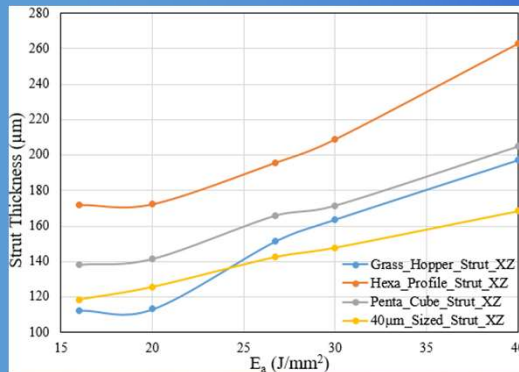
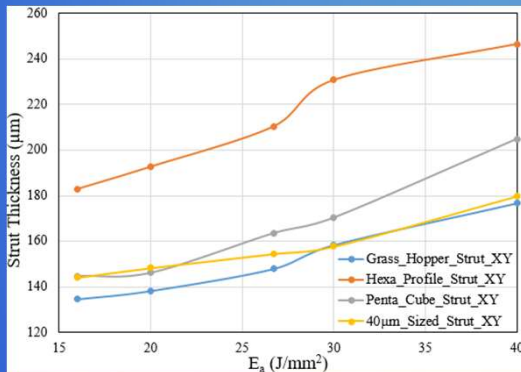
Grass Hopper W lattice, as-built in XY (top) and XZ (bottom), 200x.



W Design to Specimen Comparisons



W DOE 6 pore diameter vs. E_a based on as-built optical microscopy measurements.



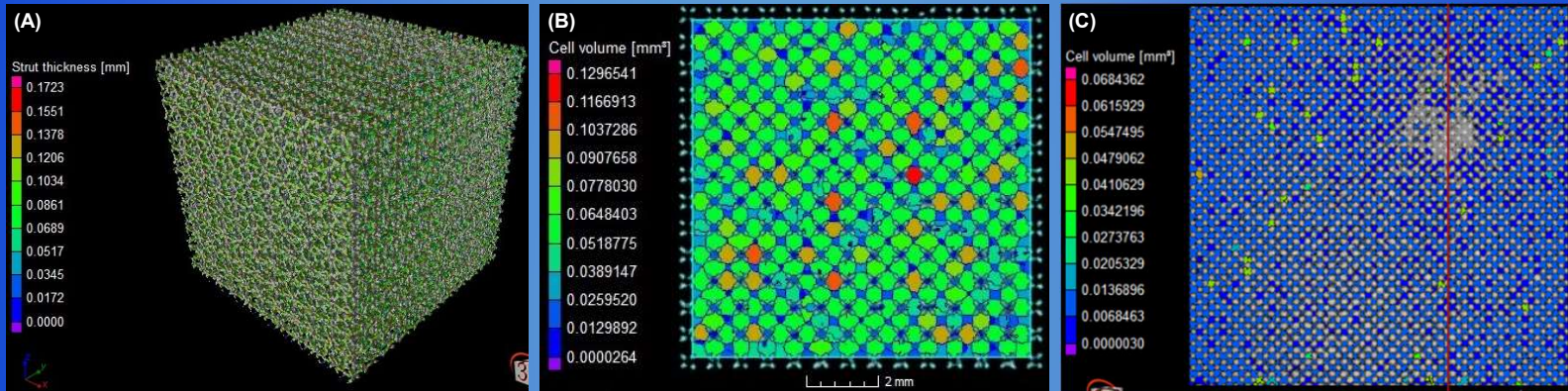
W DOE 6 strut thickness vs. E_a based on as-built optical microscopy measurements.

Median Pore Diameter	240 ± 153 μm
Median Strut Thickness	80 ± 6 μm
Lattice Unit Cell Size Range	
343 μm	Min
707 μm	Max
400 μm	Median

Lattice structure specs.

μ -CT Inspection

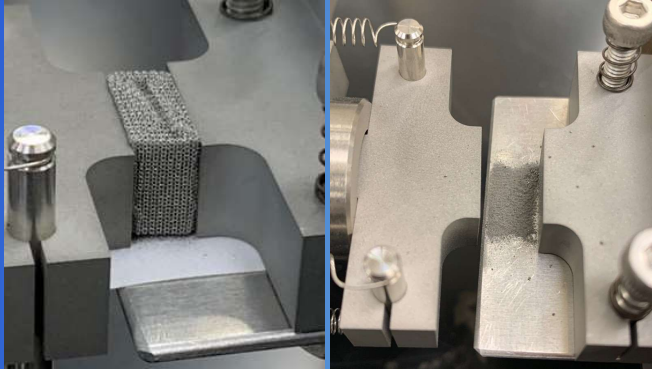
- Ti6Al4V μ -CT specimens
 - 9: Hexa (50 W, 1500 mm/s)
 - 15: Penta Cube (50 W, 1500 mm/s)
 - 29: 40 μ m Sized Surface (40 W, 1000 mm/s)
 - 33: 40 μ m Sizes Surface (50 W, 1500 mm/s)



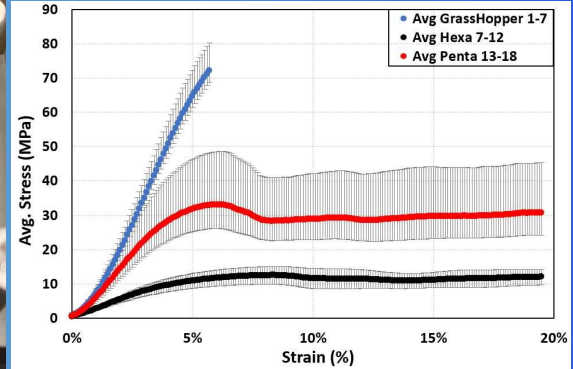
μ -CT images of Ti6Al4V Hexa specimen strut thickness (A), cell volume (B) and trapped powder (C). Courtesy 3D Engineering Solutions.

- As expected μ -CT was unable to resolve W specimens due to high scatter, low penetration depth, and poor S/N.

Mechanical Properties

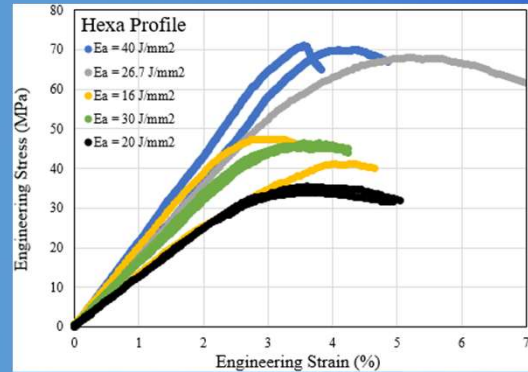
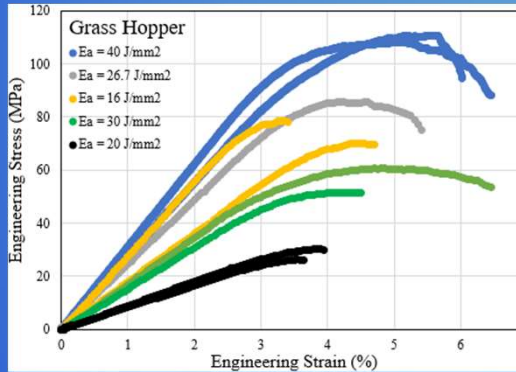
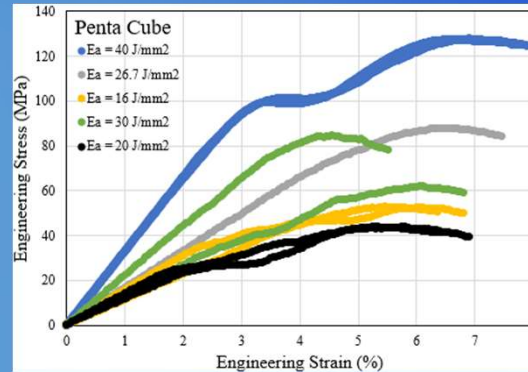
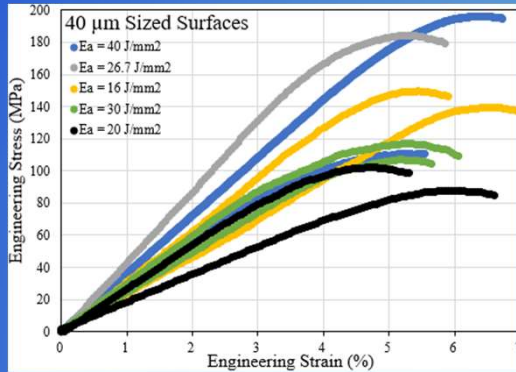


Ti6Al4V compression test using Psylotech meso-scale load frame (left) and post-test powder residue (right).



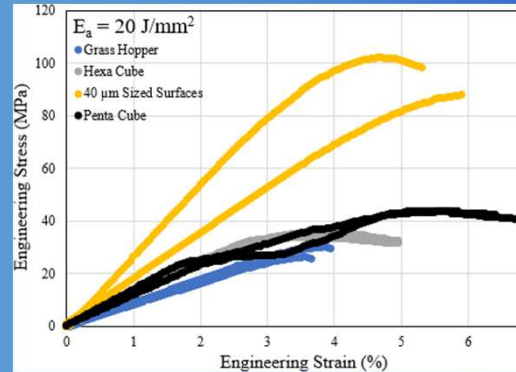
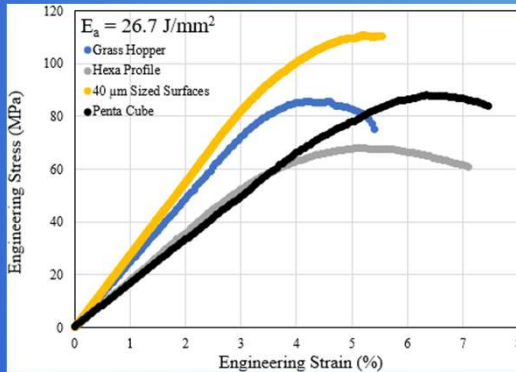
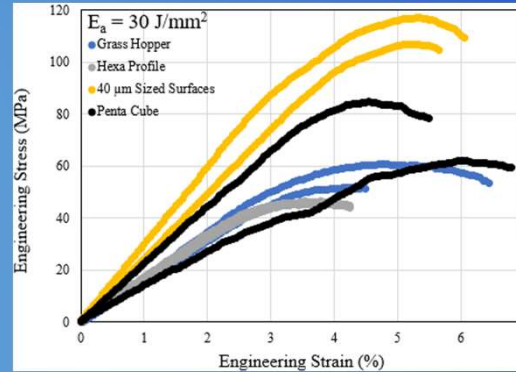
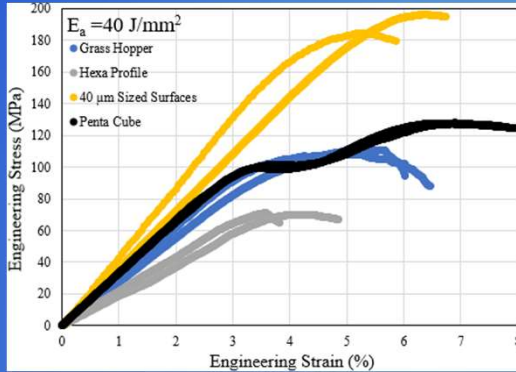
Ti6Al4V compression stress-strain diagram vs. topology type.

Mechanical Properties



Compressive stress-strain diagrams of as-built AM W DOE 6 lattice structures where topology is constant and E_a varied.

Mechanical Properties



Compressive stress-strain diagrams of as-built AM W lattice structures where E_a is constant and topology is varied.



Flow Characterization

- Conducted by the University of Texas at El Paso (UTEP)

$$K_v = Q \sqrt{\frac{\gamma}{\Delta P}} = \frac{Q}{\sqrt{\Delta P}}$$

Where:

K_v = Flow Coefficient (m^3/hr). Relative efficiency of a restriction to allow fluid through at pressure loss of 1 bar at 16 °C.

ΔP = Pressure drop across the restriction (bar).

Q = Volumetric flow rate (m^3/hr).

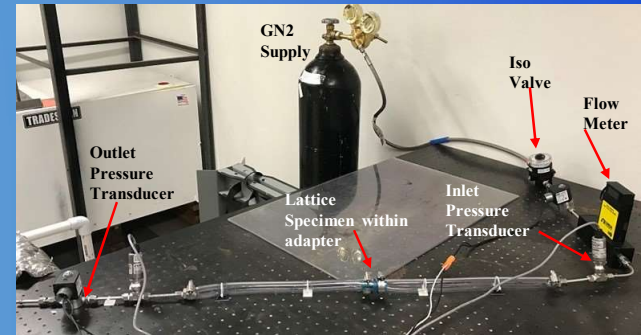
γ = specific gravity of water ($1 g/cm^3$).

$$K_v = \frac{Q}{30.8 * \sqrt{\frac{\Delta P * P_2}{\gamma * T}}}$$

K_v was also determined for subsonic nitrogen

γ = Specific gravity (kg/m^3) of nitrogen at standard conditions.

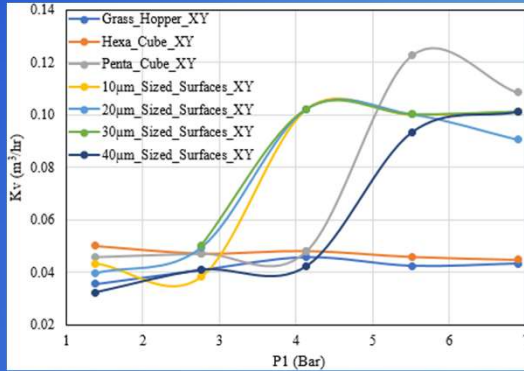
T = Absolute gas temperature (K).



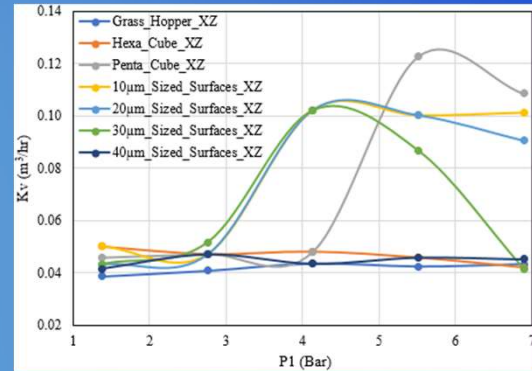
UTEP gaseous nitrogen test apparatus



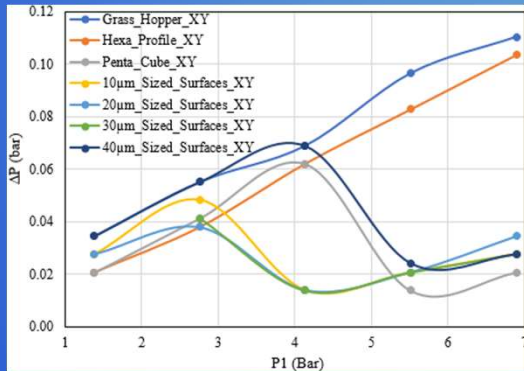
Kv and ΔP of Water



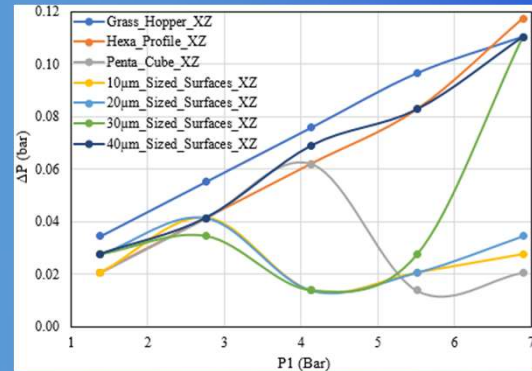
Kv for water of Ti64Al4V specimens in XY plane.



Kv for water of Ti64Al4V specimens in XZ plane.



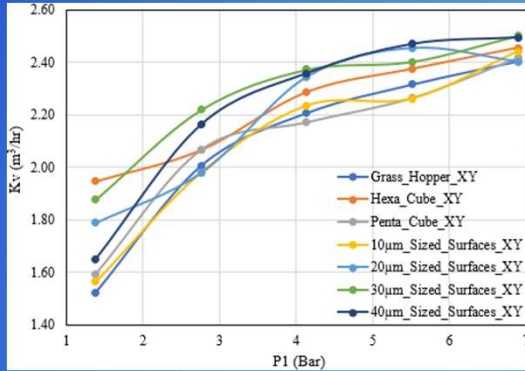
ΔP for water of Ti64Al4V specimens in XY plane.



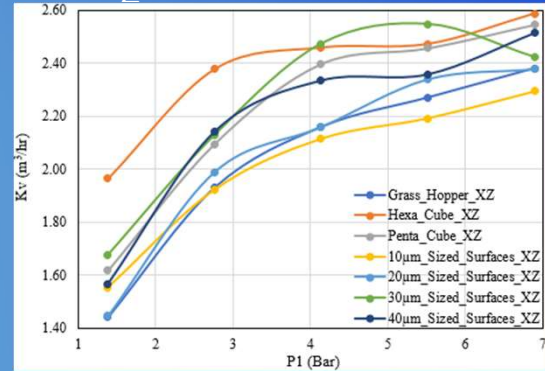
ΔP for water of Ti64Al4V specimens in XZ plane.



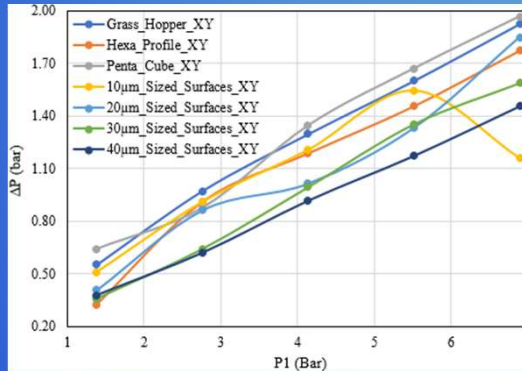
Kv and ΔP of GN₂



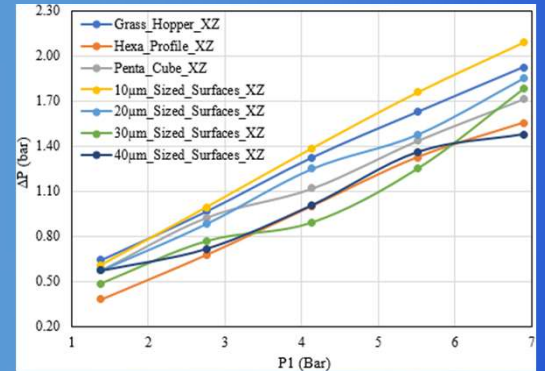
Kv for GN₂ of Ti64Al4V specimens in XY plane.



Kv for GN₂ of Ti64Al4V specimens in XZ plane.



ΔP for GN₂ of Ti64Al4V specimens in XY plane.



ΔP for GN₂ of Ti64Al4V specimens in XZ plane.



Conclusions

- Results

- AM Ultra fine lattices are viable.
- Nearly all geometries produce stable results for Ti6Al4V with 50 W and 1500 mm/s.
- Seven lattice topologies were found to be functional for Ti6Al4V.
- Four lattice topologies were found to be functional for W.
- Mechanical and flow properties were as good or better over traditional foam products.

- Recommendations for future work

- Develop print parameters catalytic materials such as Rhodium and Iridium alloys.
- Optimize parameter and post processing steps to yield ultra-fine lattice structures from catalytic alloys.
- Develop methods for improved powder removal from lattice cell volume (i.e. ultrasonic or chemical).
- Characterize compressive and flow properties of AM lattice catalysts.
- Propellant flow tests through AM lattice catalyst.
- Integrate AM lattice catalysts into AM refractory alloy thruster body and hot fire test campaign is needed to increase TRL for flight implementation.



Acknowledgements

- The authors would like to thank Daniel Cavender, Marvin Barnes, Trevor Bormann, and Jason Turpin of NASA MSFC; Ankit Saharan of EOS North America, 3D Engineering Solutions; Edel Arrieta, Raul Cuevas, Pilar Gonzalez, Frank Medina, Jaclyn Mejia, and Jonathan Navarrete of UTEP.
- This project was funded under NASA Cooperative Agreement Notice #80MSFC19M0002.
- The opinions expressed in this presentation are those of the author and do not necessary reflect the views of NASA or any NASA Project.

