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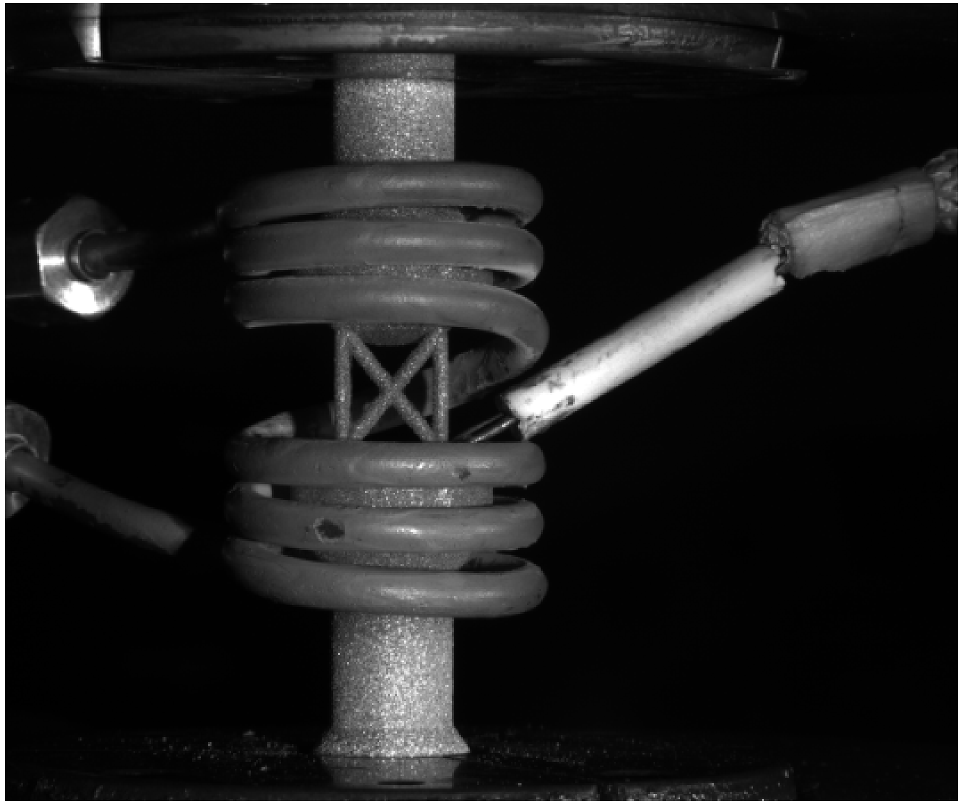
CLEMSON UNIVERSITY

# The Deformation and Buckling of FCCZ Metamaterials via Creep at Elevated Temperatures

Sandia National Laboratories

Kaitlynn M. Fitzgerald[1,2], Garrett J. Pataky[1], Tom Berfield[3], Hamid Sarraf[4]

[1]Clemson University
[2]Sandia National Labs
[3]University of Louisville
[4]Purdue University



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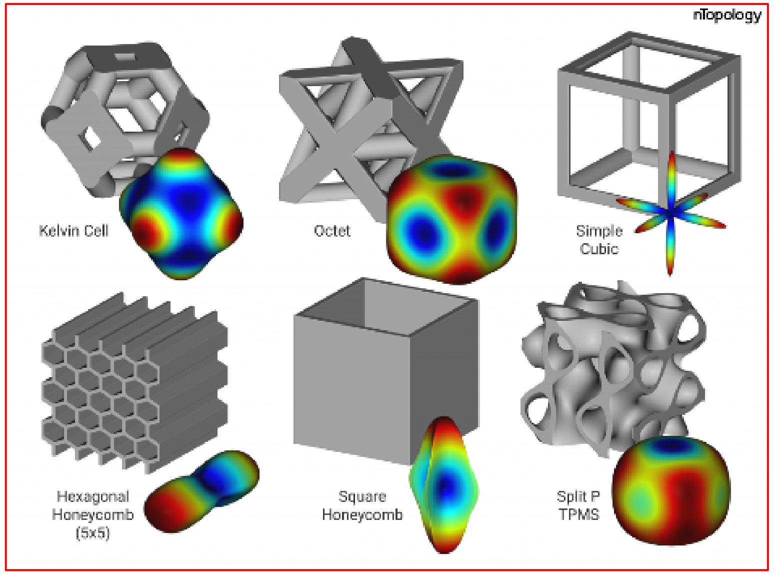
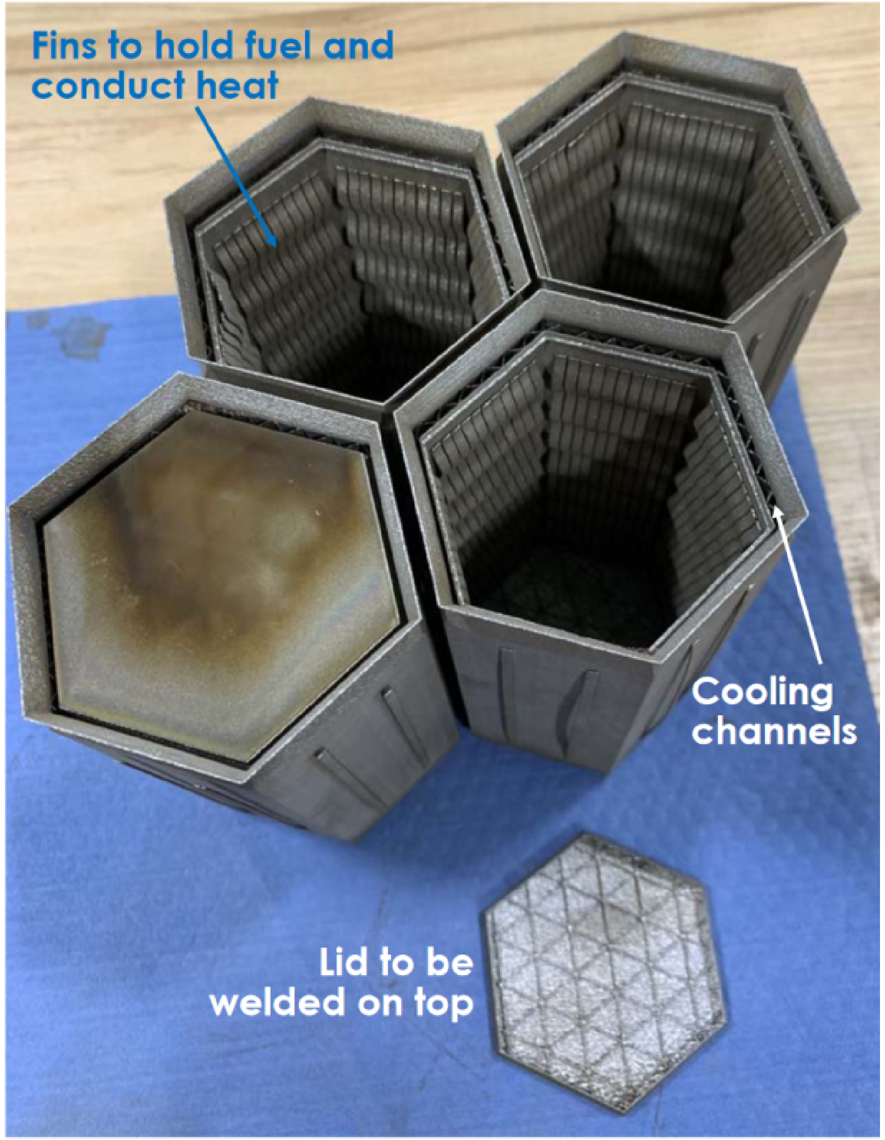
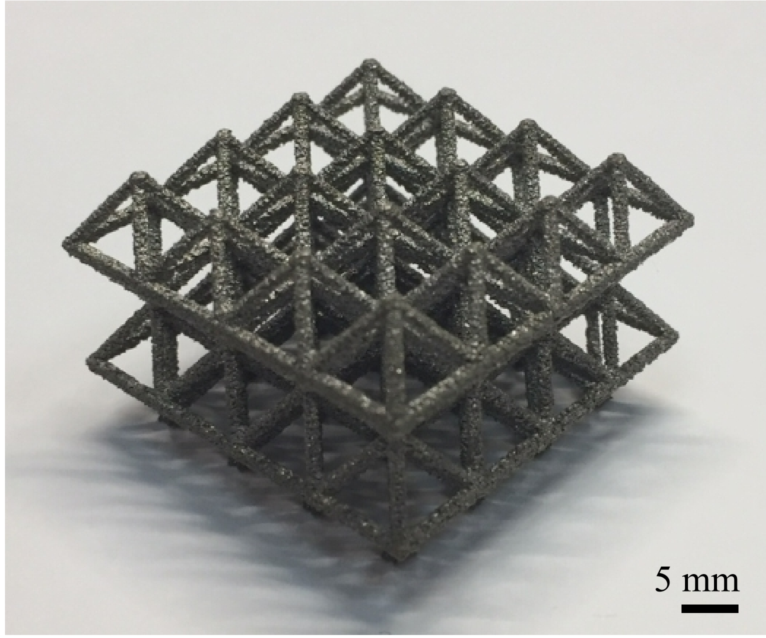
# Metamaterials - Decreasing Weight and Enhancing Functionality

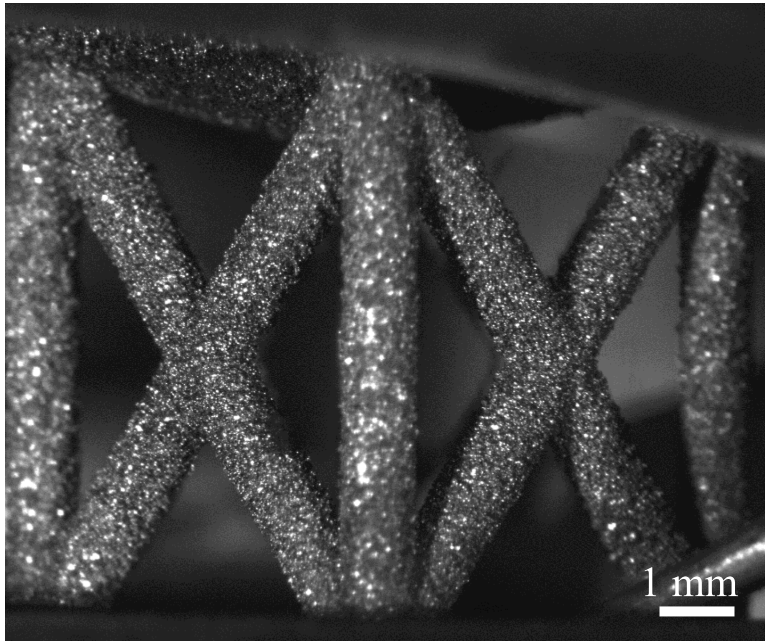



- AM allows integrated design and manufacturing efforts to enhance deployment time
- Enables complex topologies not traditionally possible with subtractive manufacturing




Source: ORNL




# Metamaterials at Elevated Temperatures

- Targeted material properties able to include multifunctionality.
- Limited by lack of understanding of fracture and failure behavior

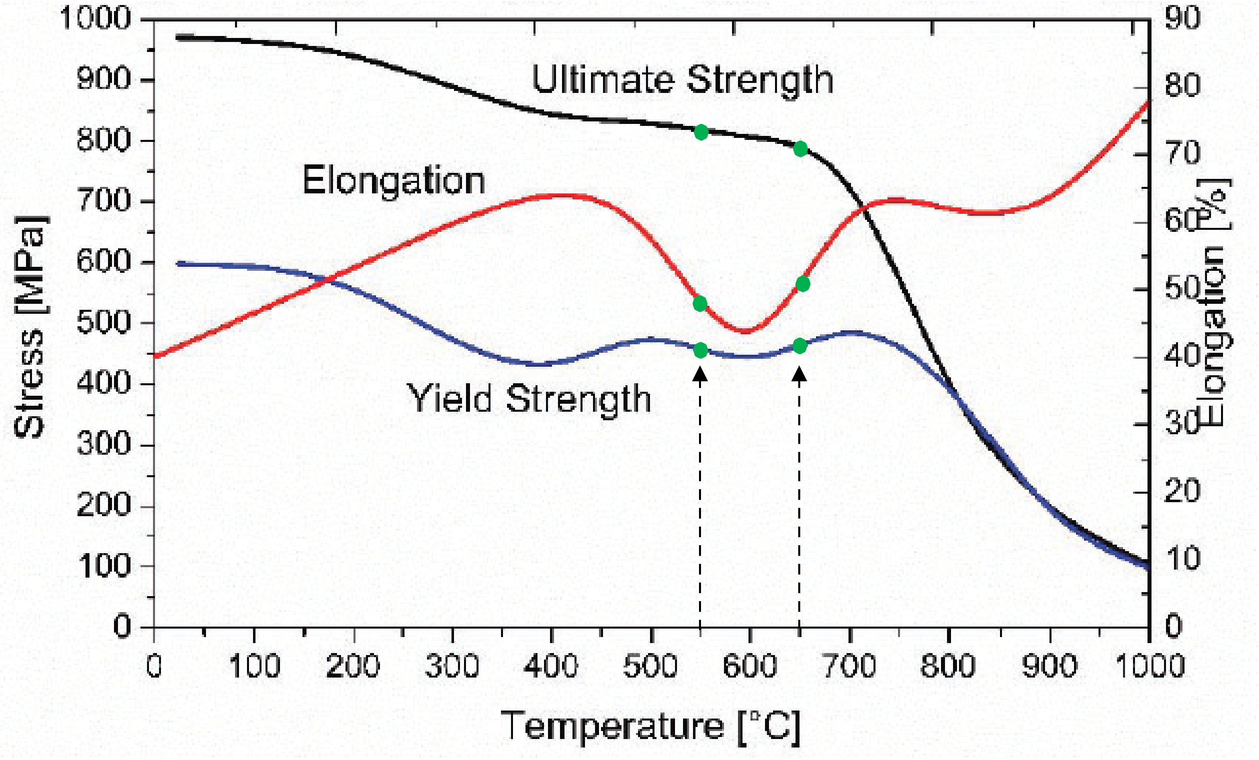
Does the base material creep behavior or topology dominate the failure of the FCCZ lattices?

What is the stress dependence of the failure mode?

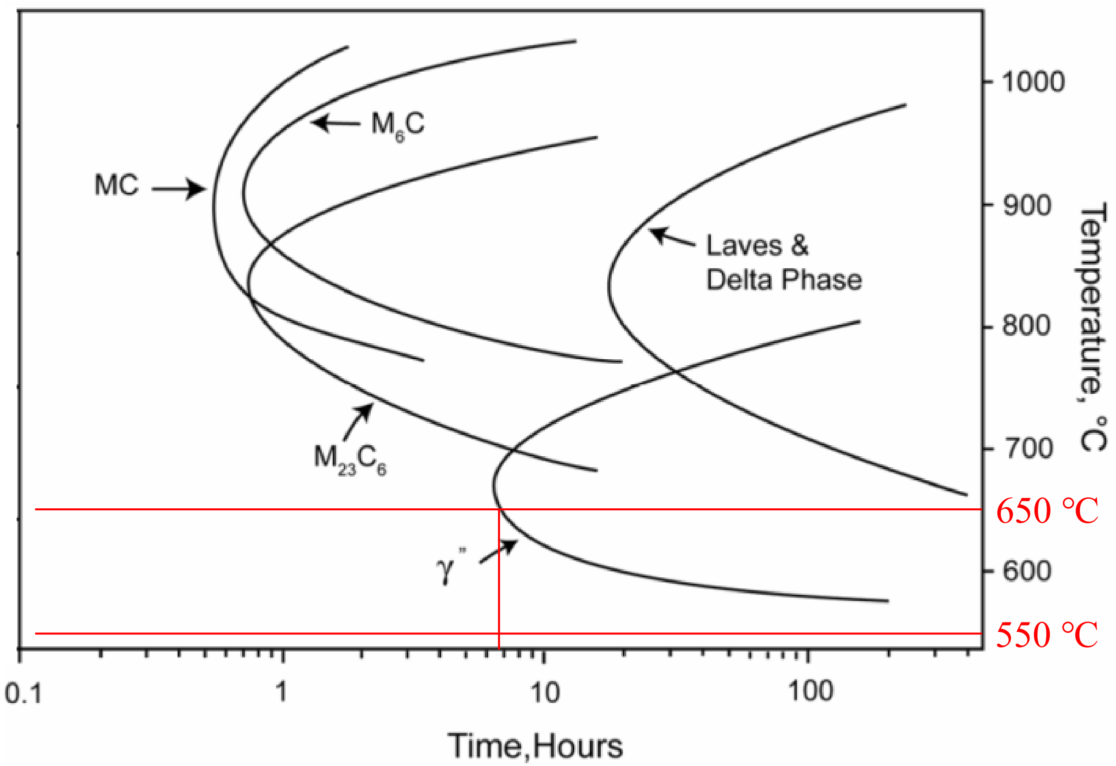

Specimen held at temperature for 5 min before test started

| Specimen | Temperature | Test Type | Stress |
|---|---|---|---|
| Flat Dog Bone (Area = 16.46 $mm^2$) | Ambient | Uniaxial (Tension) | NA |
| | 550 °C | | |
| | 650 °C | | |
| Round Dog Bone (Area = 21.48 $mm^2$) | 550 °C | Creep (Compression) | 35% Yield |
| | | | 50% Yield |
| | | | 65% Yield |
| | 650 °C | Creep (Compression) | 35% Yield |
| | | | 50% Yield |
| | | | 65% Yield |
| Lattice (Area = 12.46 $mm^2$) | Ambient | Uniaxial (Compression) | NA |
| | 450 °C | | NA |
| | 550 °C | | NA |
| | 650 °C | | NA |
| | 550 °C | Creep (Compression) | 35% Yield |
| | | | 50% Yield |
| | | | 65% Yield |
| | 650 °C | | 35% Yield |
| | | | 50% Yield |
| | | | 65% Yield |

# Inconel 625 at 550°C and 650°C




de Olveira et al., Metals, 2019

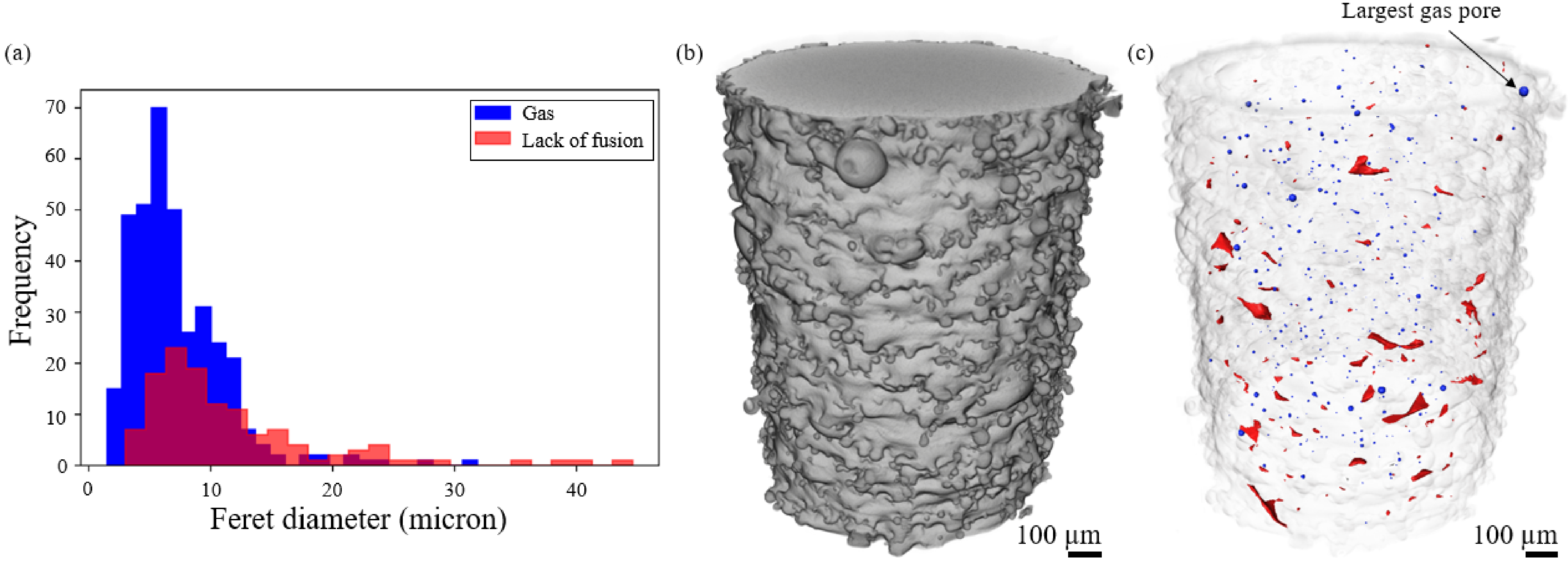



Shoemaker, Superalloys, TMS, 2005

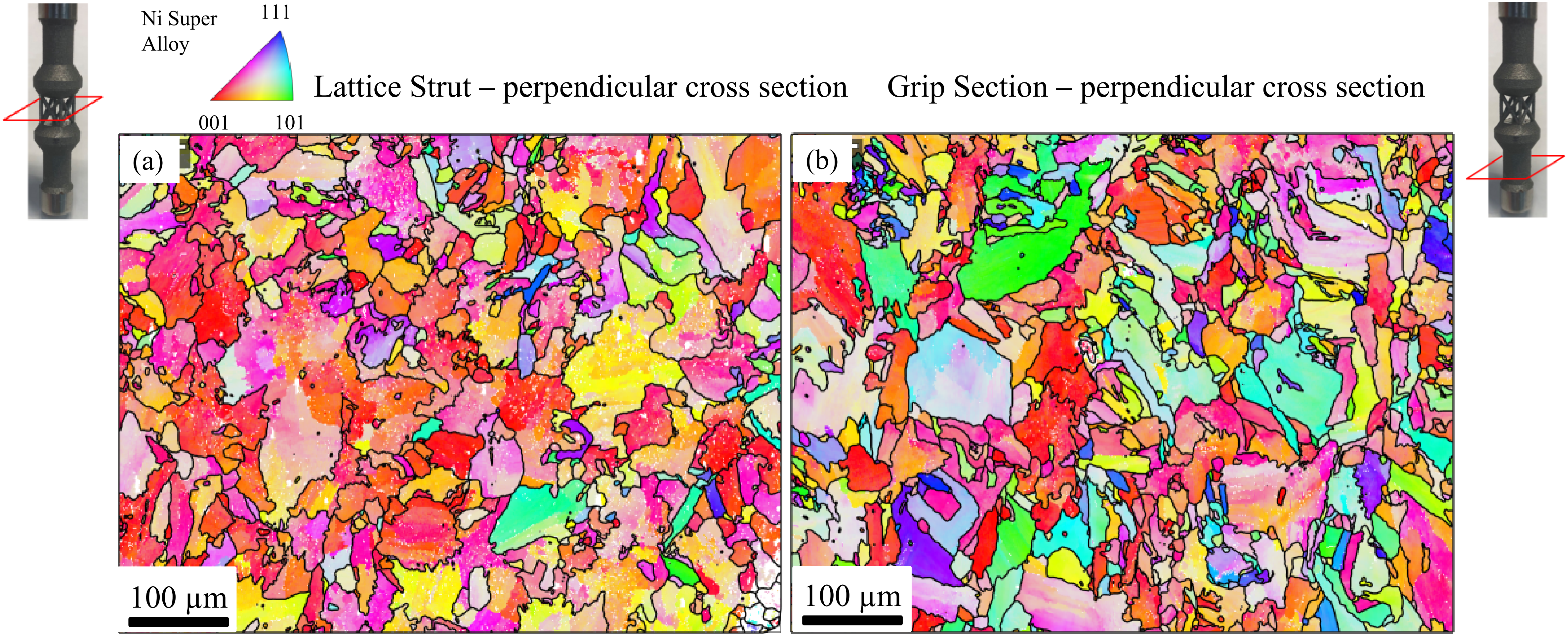
- Inconel 625 is solid solution hardened alloy with an FCC γ matrix
- Only small changes in material properties between 550 °C and 650 °C
- Ductility loss at 600 °C

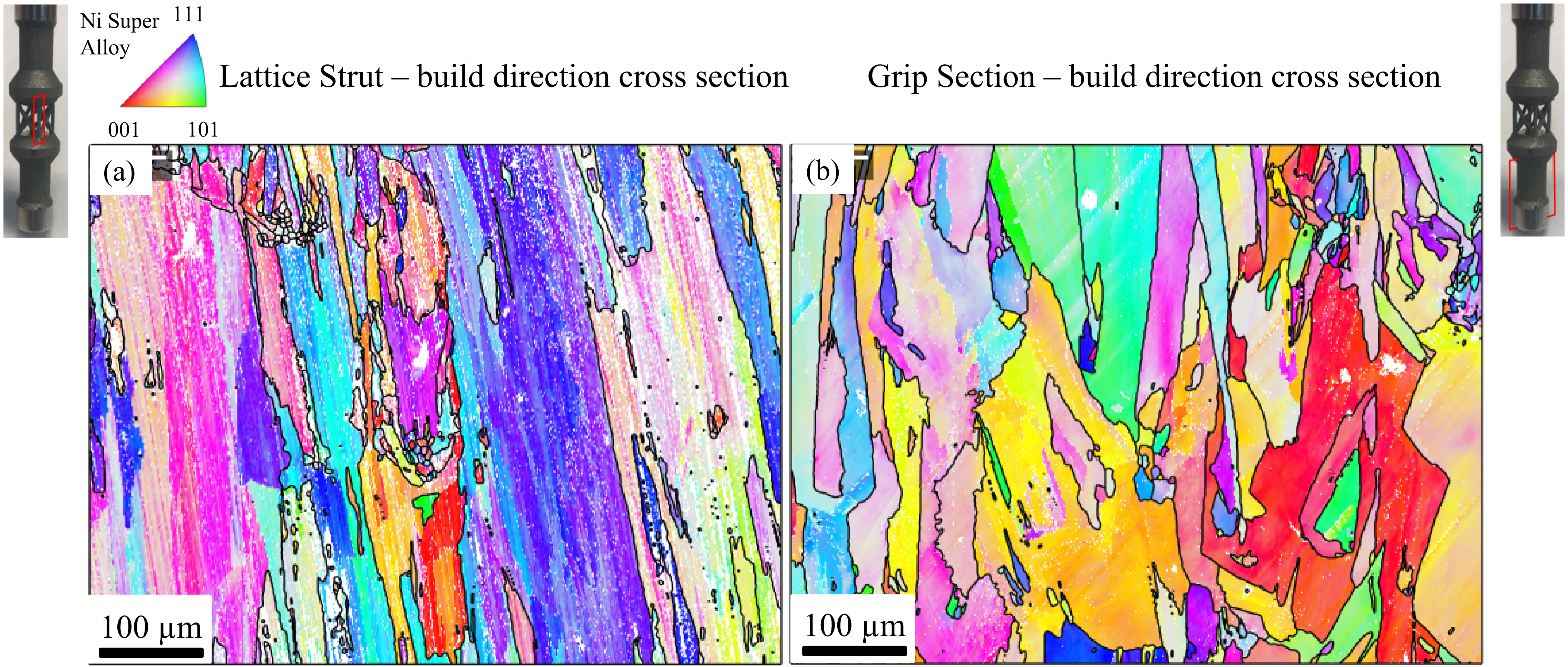
- Change in creep rate due to γ''
- At 550 °C no short term precipitates
- At 650 °C precipitates γ'' (body-centered tetragonal) in ~7 hours

# X-ray Computed Tomography – Lattice Z Strut



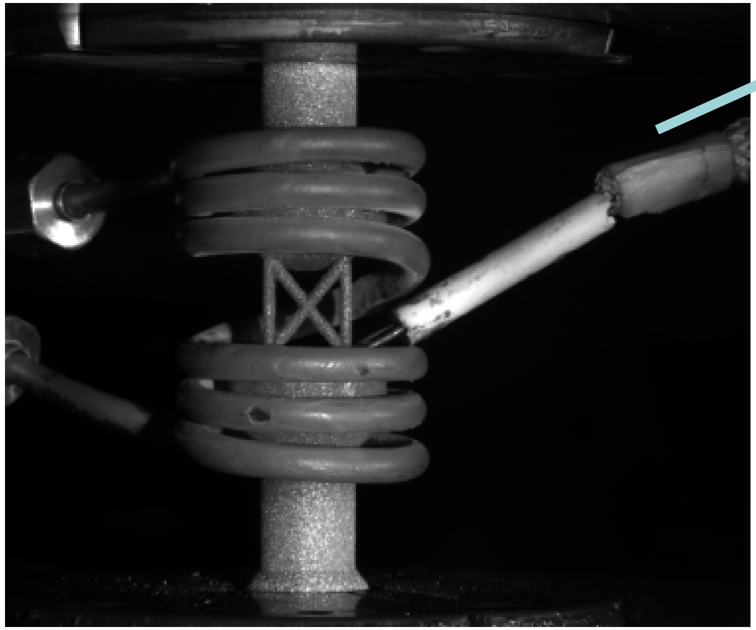

- 99.9% dense
- Sphericity index used to define difference between defects

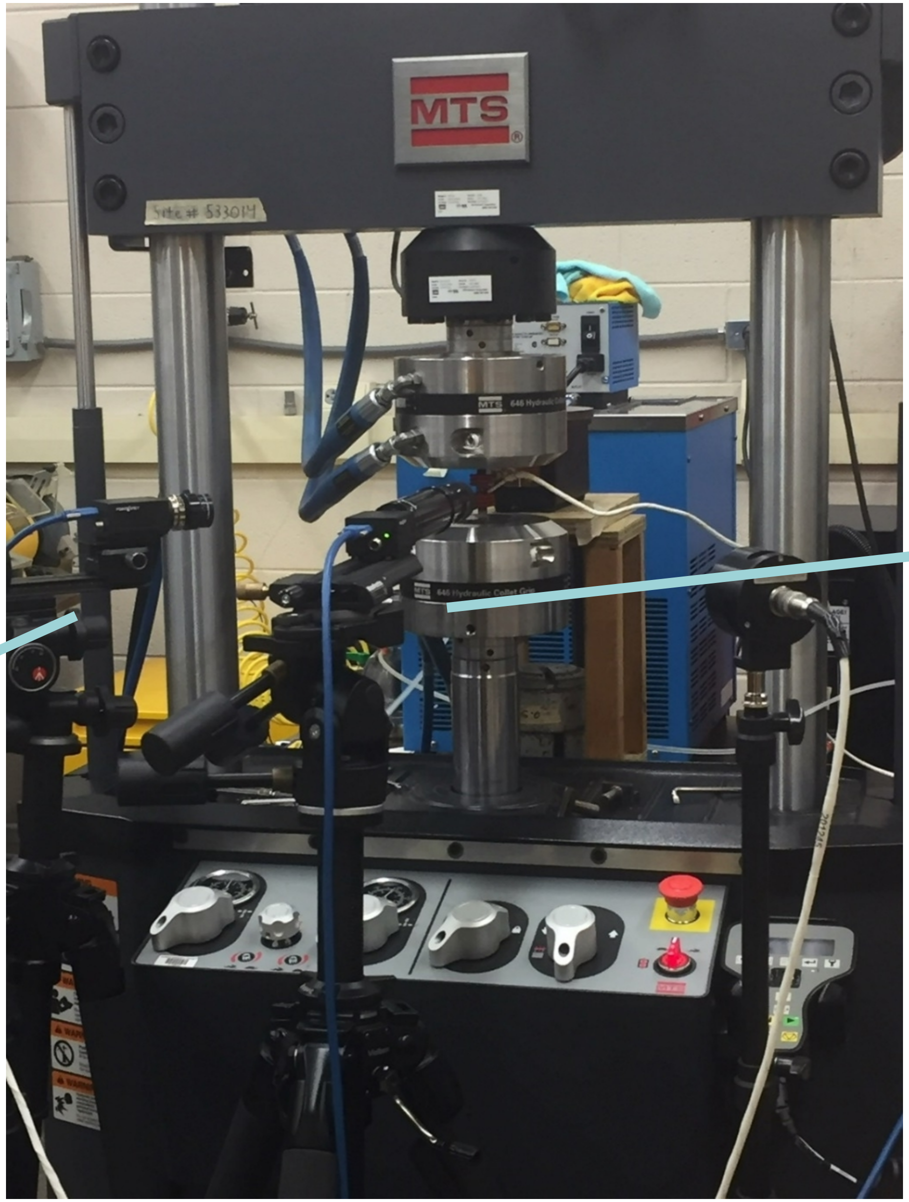

Ni Super Alloy
111
001
101
Lattice Strut – perpendicular cross section
Grip Section – perpendicular cross section
(a)
100 µm
(b)
100 µm

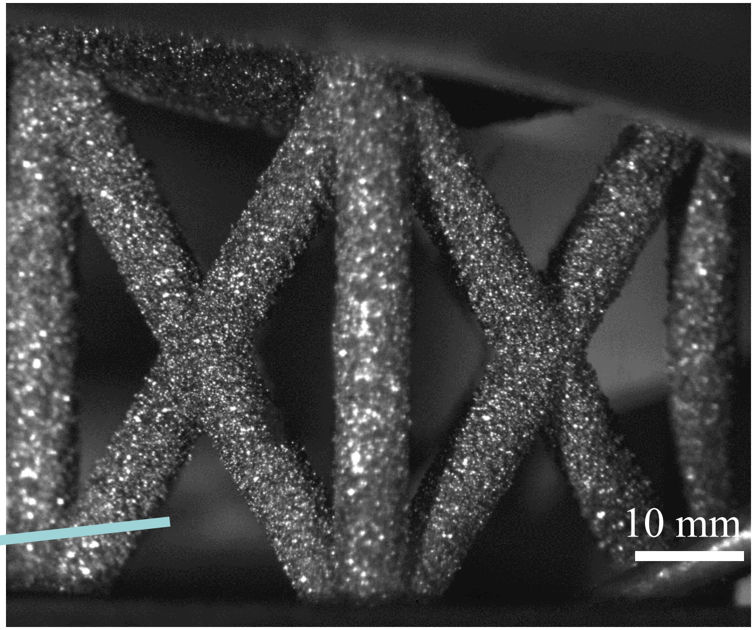



| Specimen | Average Aspect Ratio | Average Length of Grain Major Axis (µm) |
|---|---|---|
| Lattice - build direction | 5.5 | 59.2 |
| Lattice - perpendicular | 2.1 | 31.7 |
| Grip section - build direction | 4.0 | 53.2 |
| Grip section - perpendicular | 2.3 | 28.2 |

# Experimental Setup

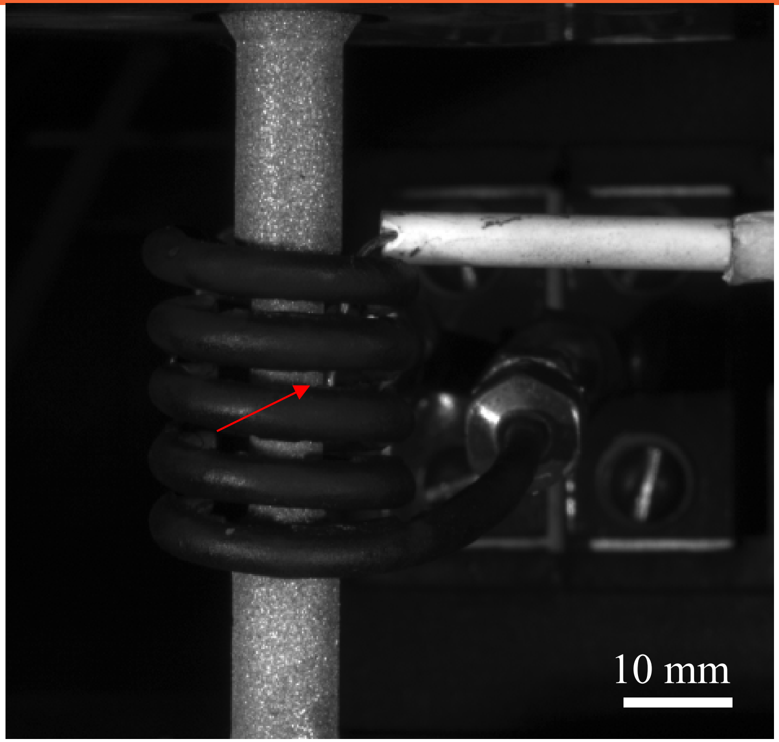


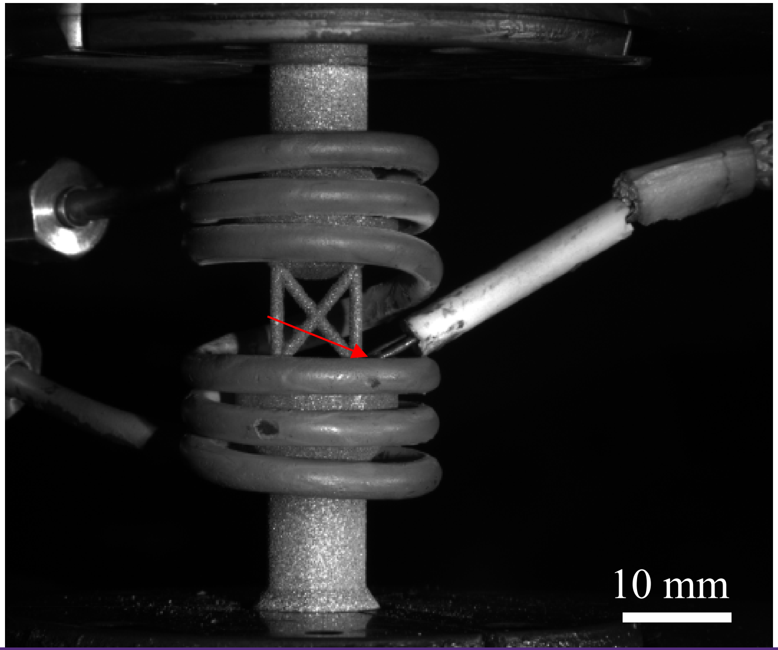



- 2 Camera setup – local and global for DIC

- Induction heating

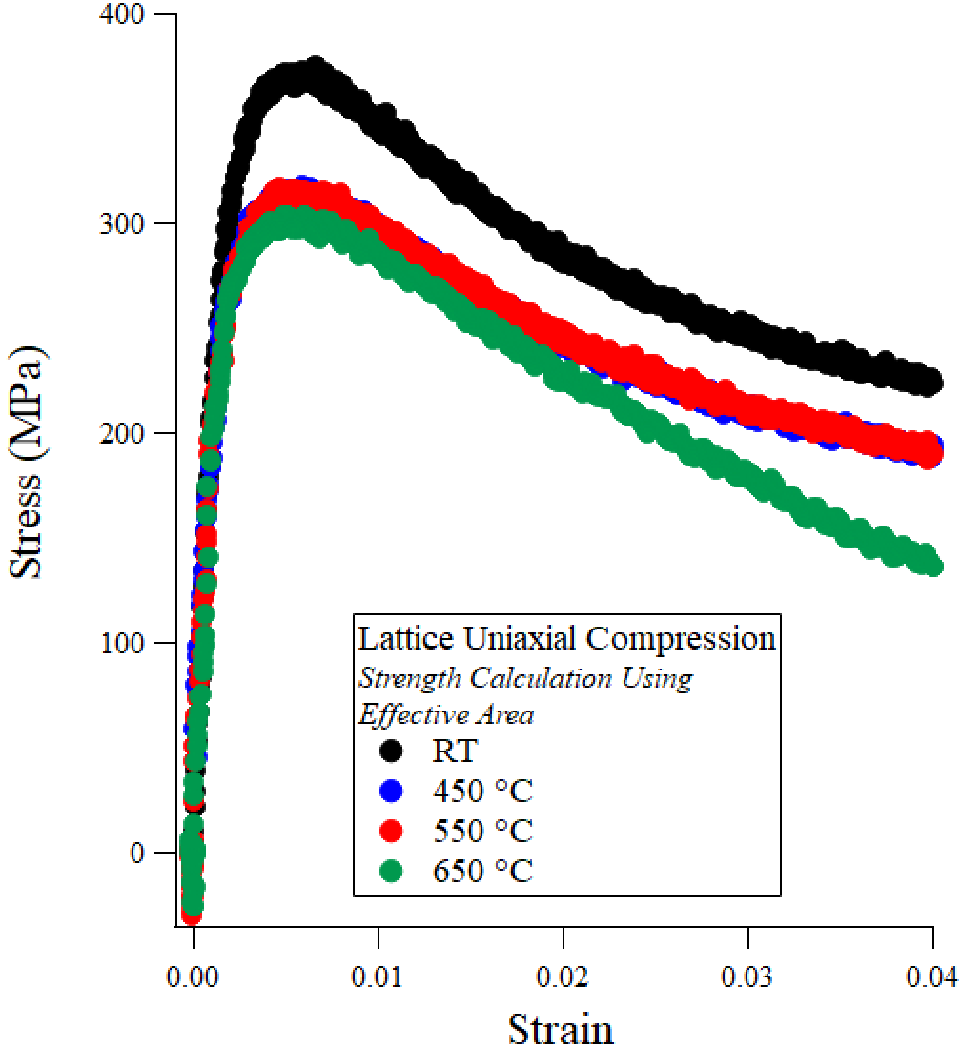



# Specimen Setup


- Thermocouple welded to specimen at hottest location – Welded below strut
- Blue light filter
- As printed surface used as speckle pattern
- Specimen held at temp 5 min before testing

## Material Characterization

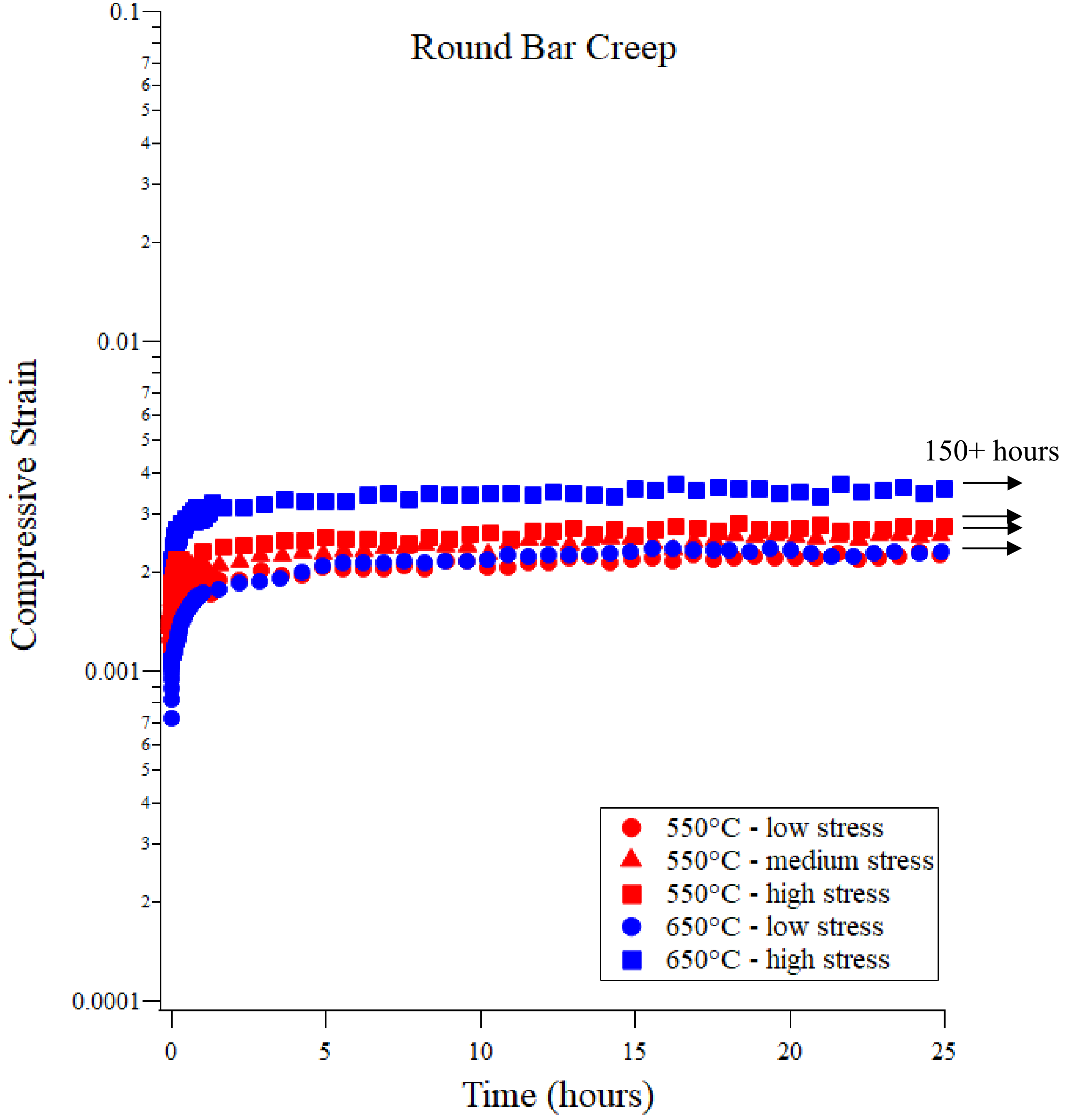


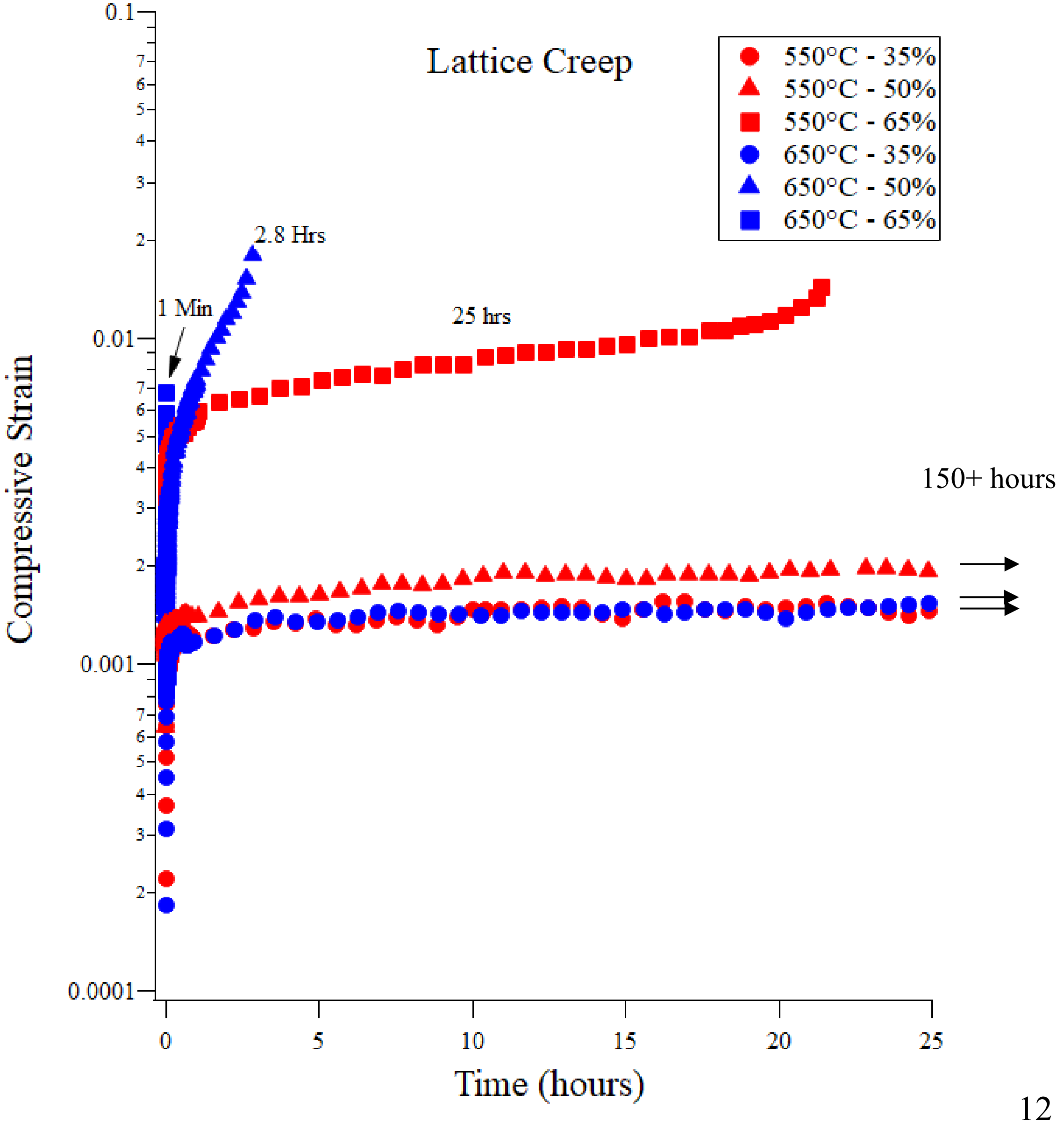

### Flat Dog Bone - Tension

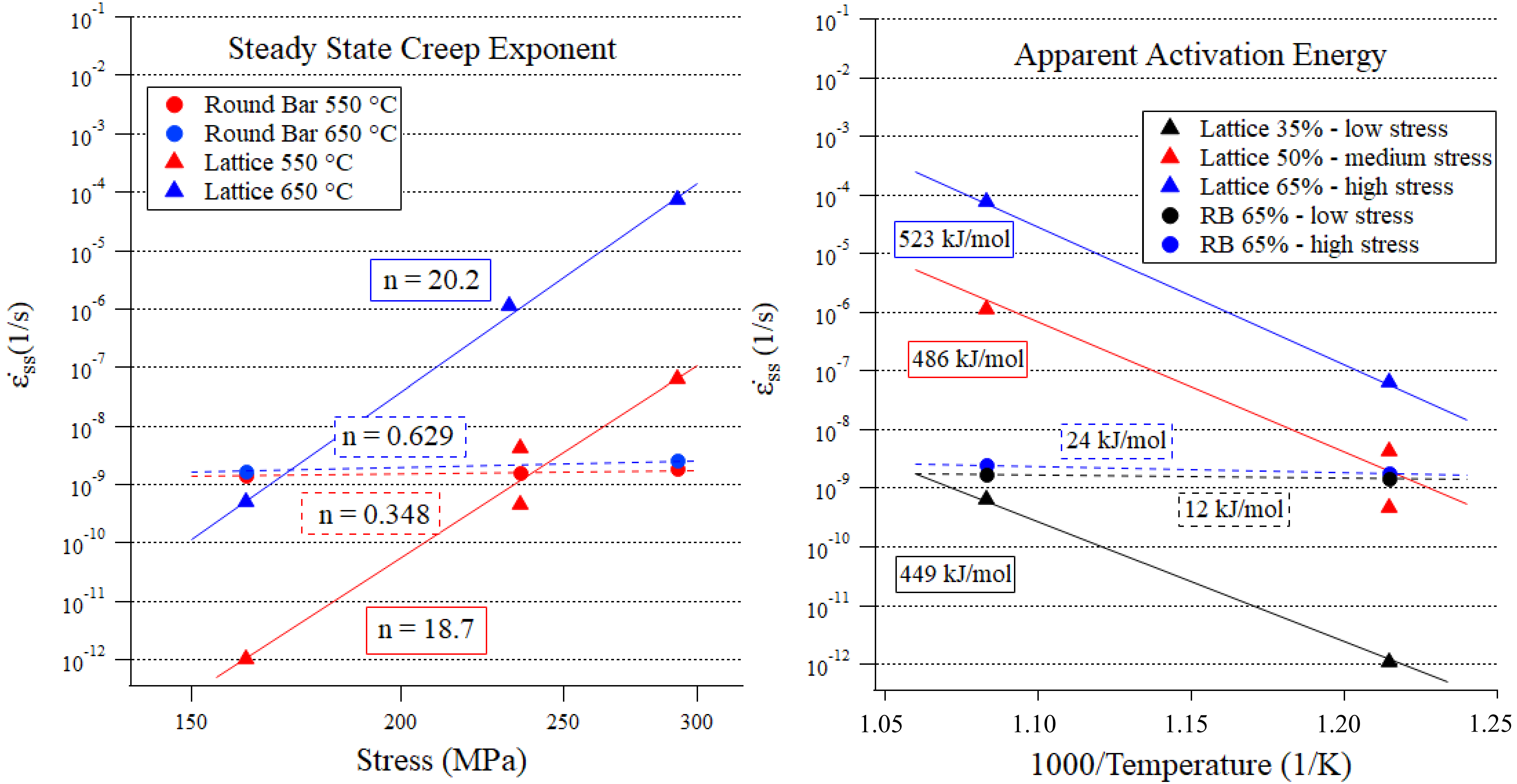
| Temperature °C | Yield Strength (MPa) | Stiffness (GPa) |
|---|---|---|
| Ambient | 503 | 216 |
| 450 | 471 | 137 |
| 550 | 450 | 111 |
| 650 | 455 | 91 |

| Temperature °C | Max Force (kN) | Yield Strength (MPa) | Stiffness (GPa) |
|---|---|---|---|
| Ambient | 4.68 | 375 | 217 |
| 450 | 3.96 | 318 | 117 |
| 550 | 3.95 | 317 | 135 |
| 650 | 3.79 | 304 | 139 |

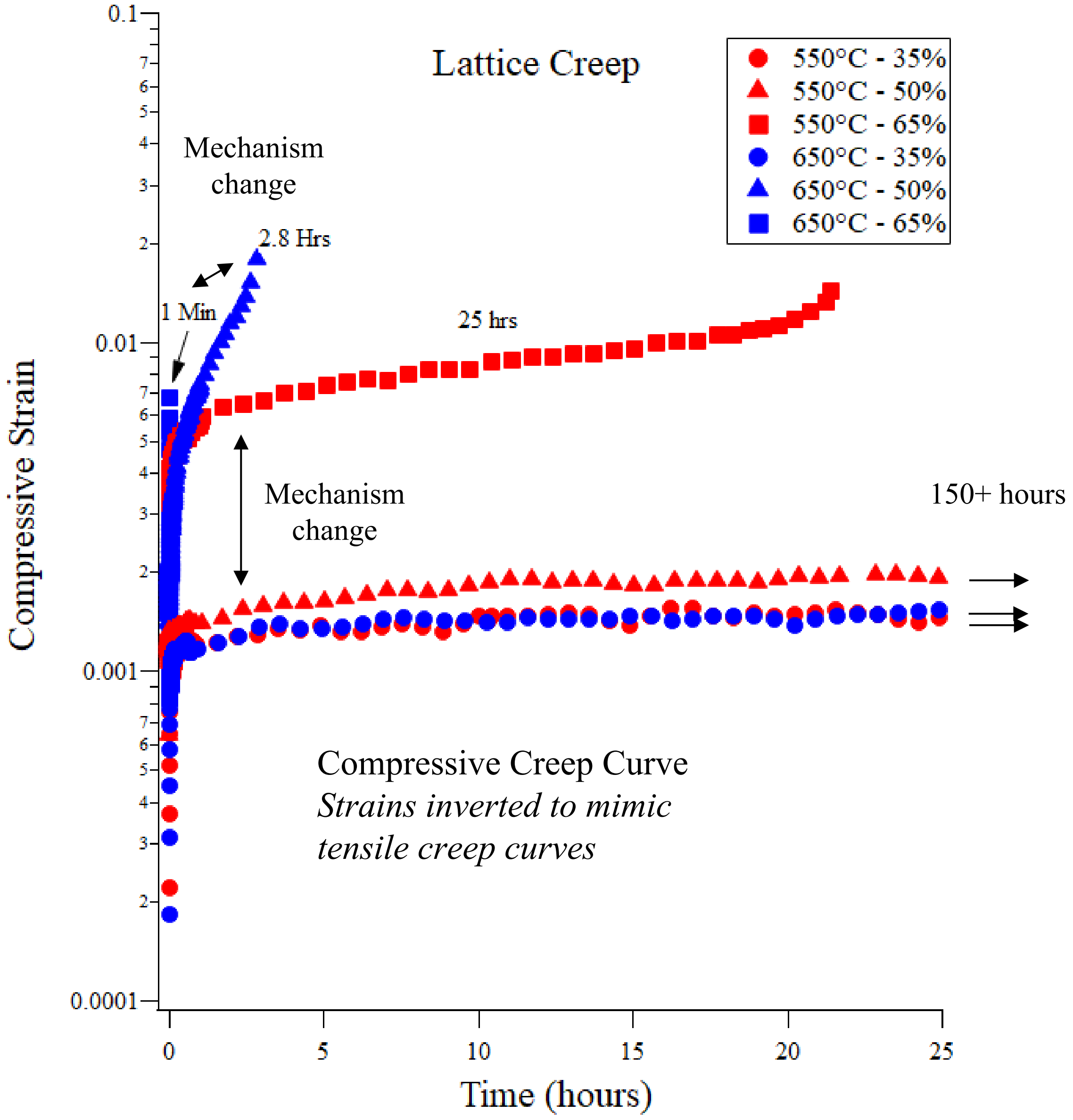
# Lattice "stability" more dependent on stress and temperature than solid bars






Lattice: Two orders of magnitude larger creep rate than round bar. Temperature and stress have large change in lattice response

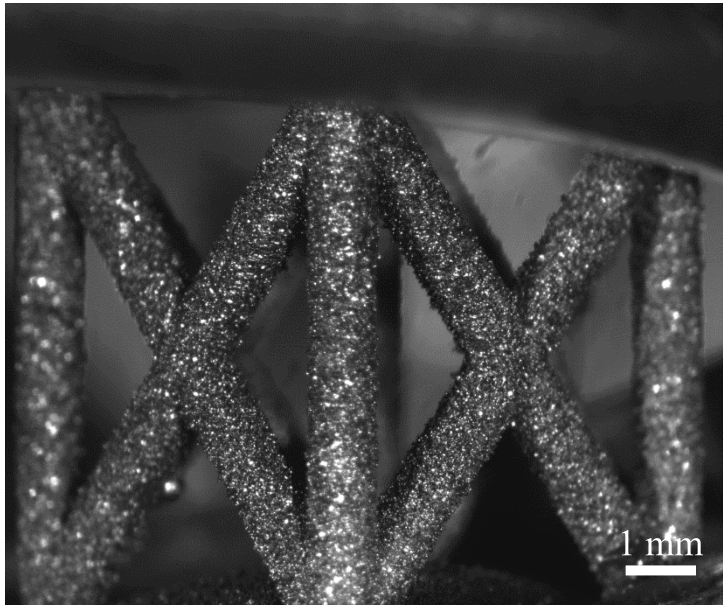


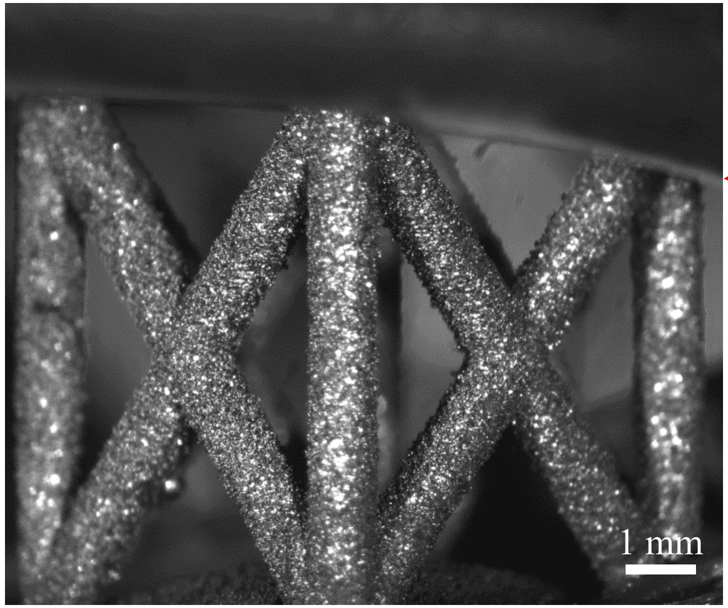

## Mechanistic Changes

- Three different time scales, seconds, hours, days
- Deformation mechanism changes and large difference in primary creep strain

550 °C - 50%

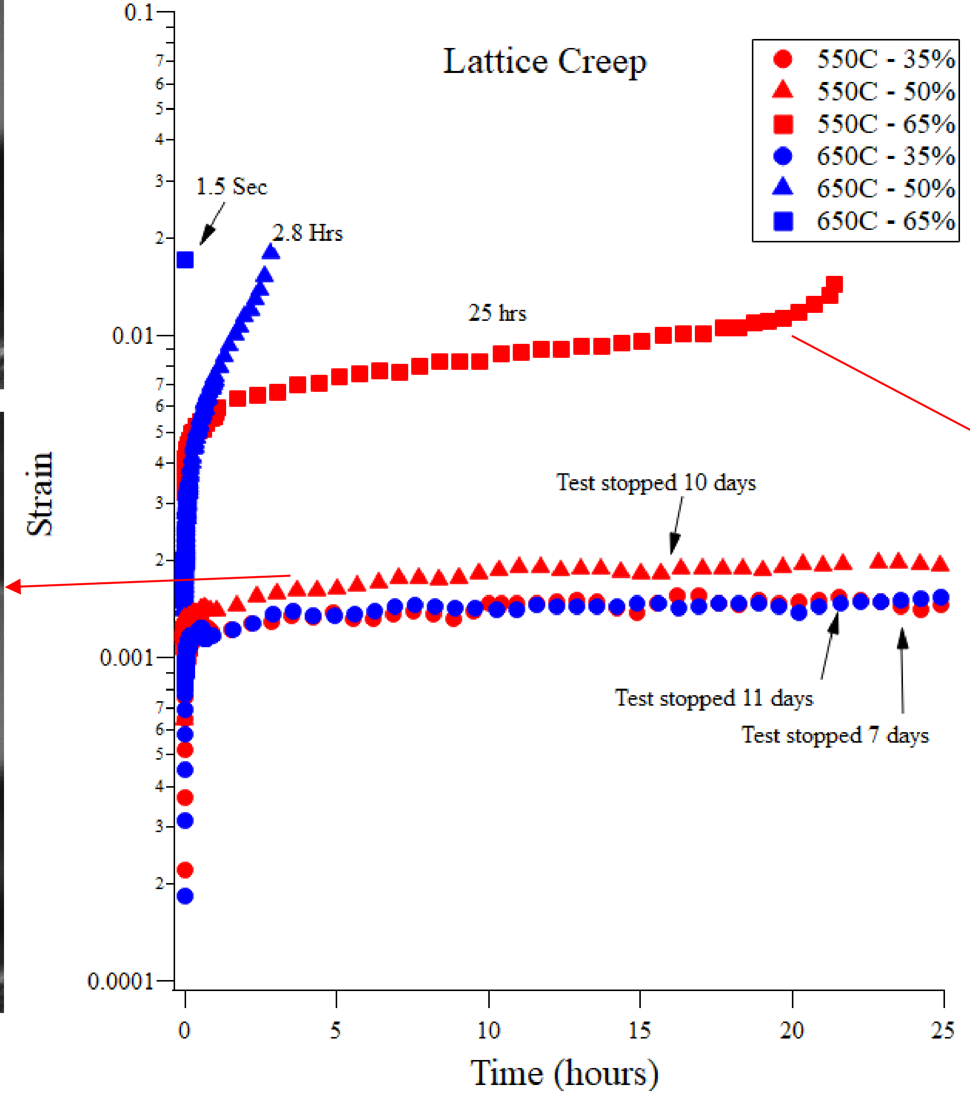
Unloaded



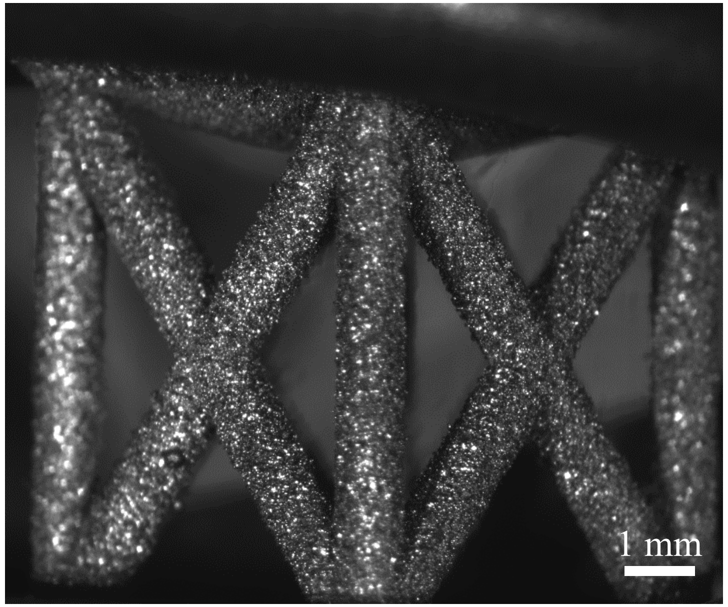



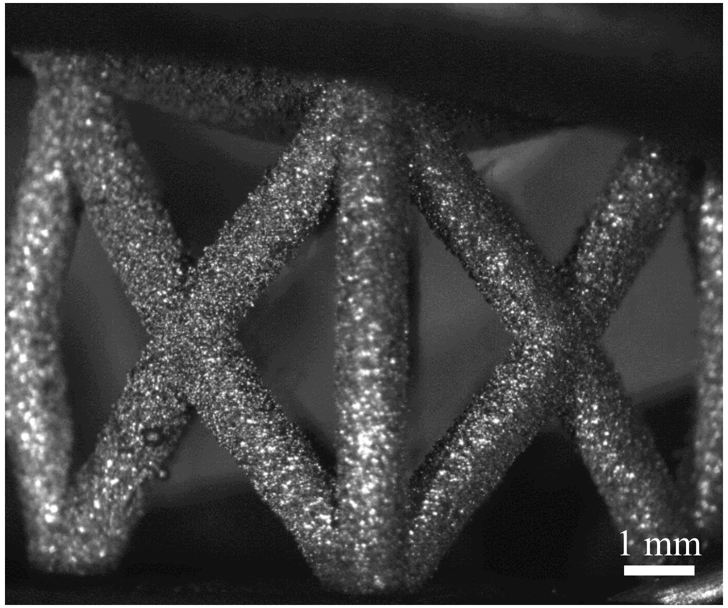

218 hours

- **550 °C - 50%** - No bending detected
- **550 °C - 65%** - Bending detected after initial loading

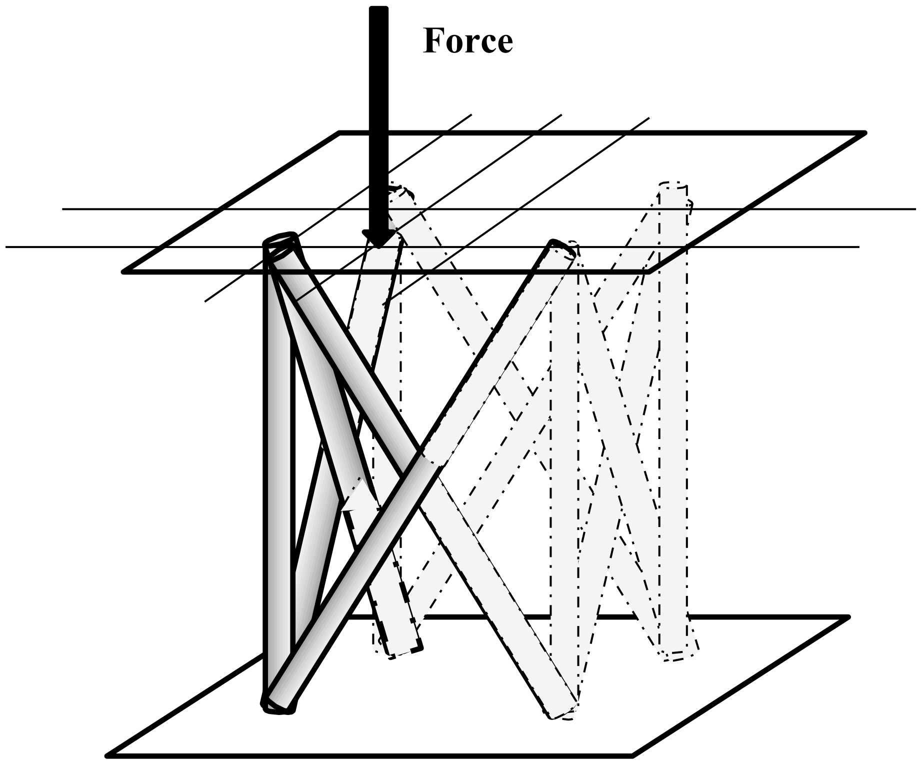



550 °C - 65%



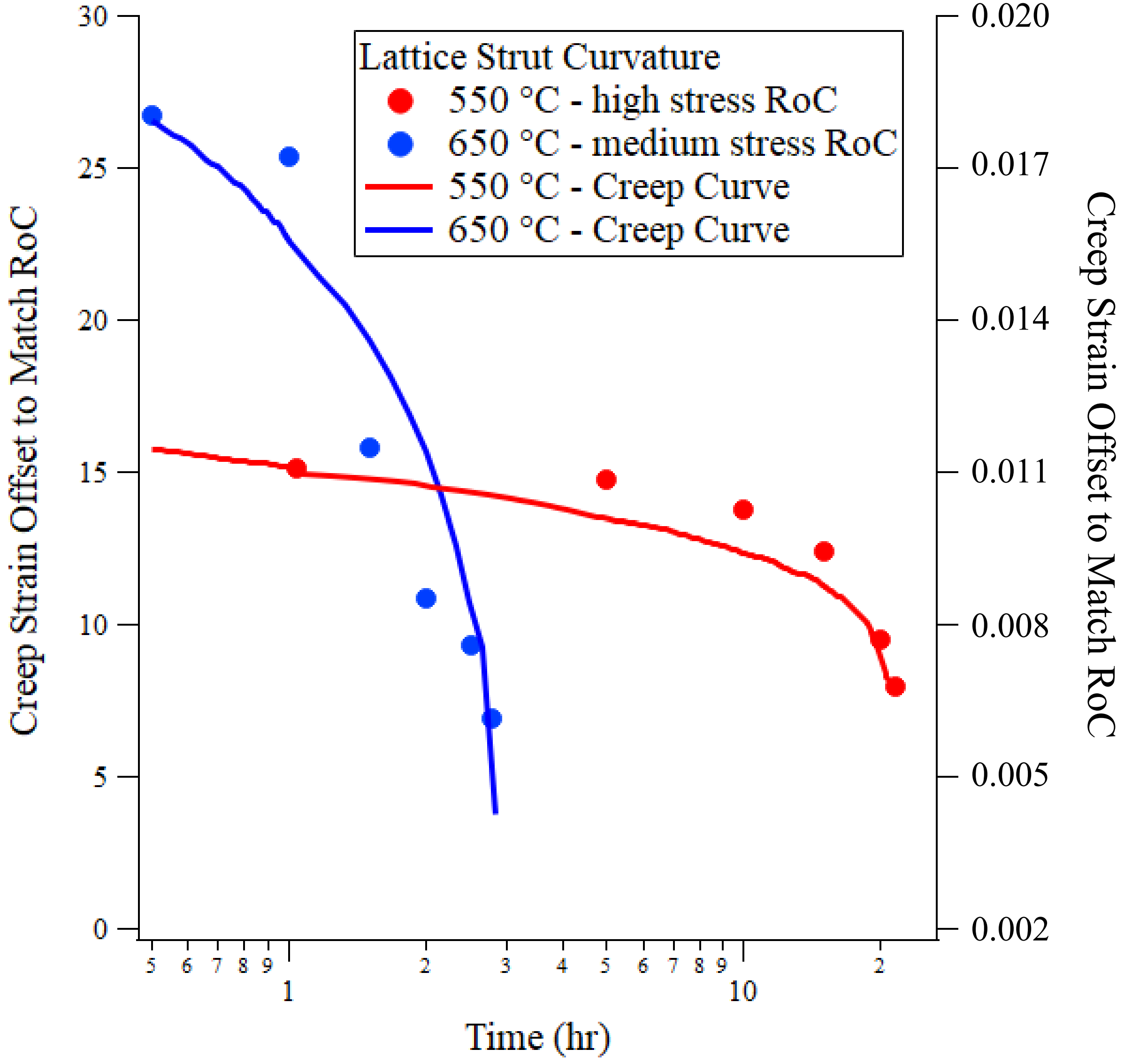




25 hours



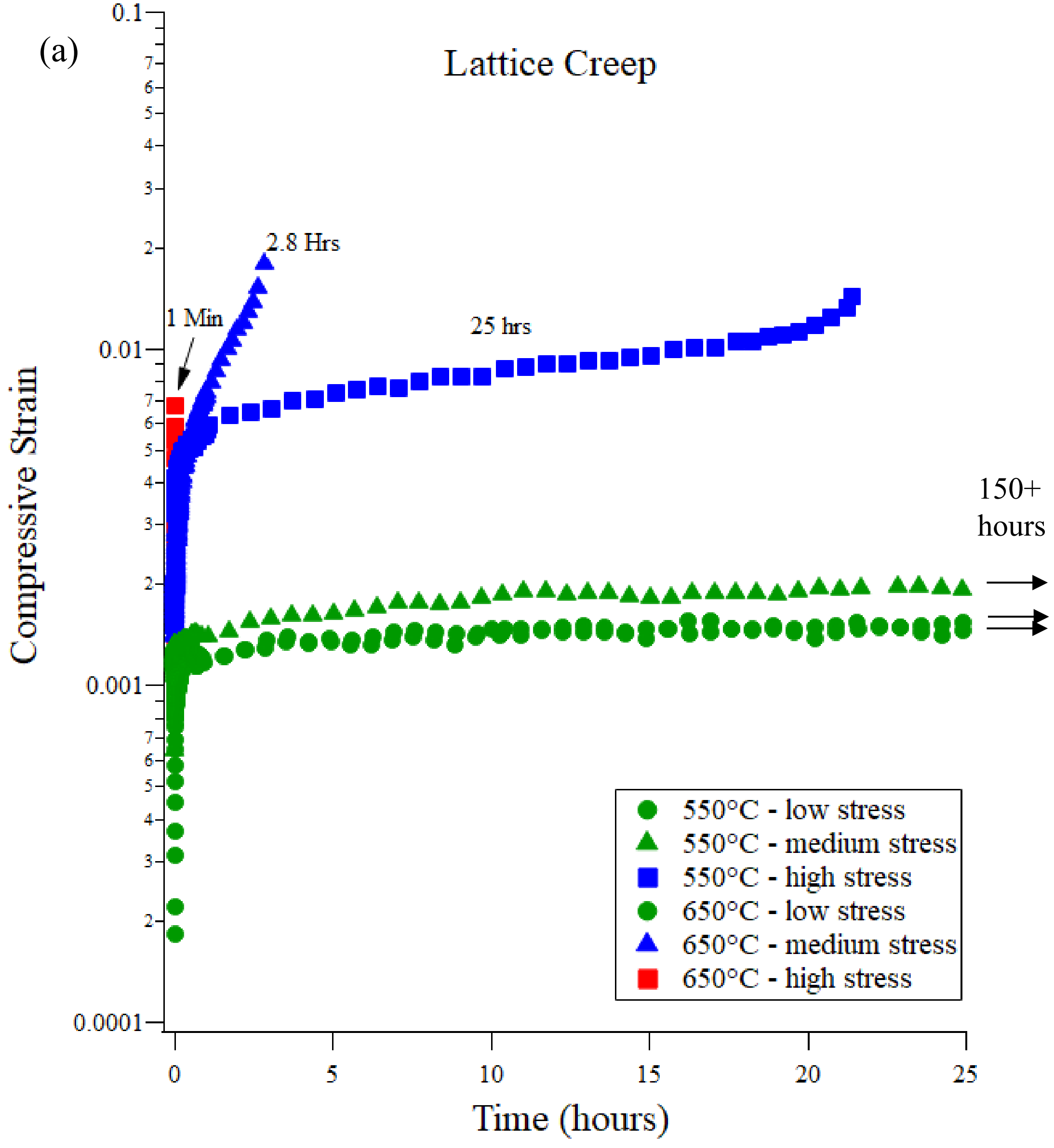

# Euler Beam Creep Buckling

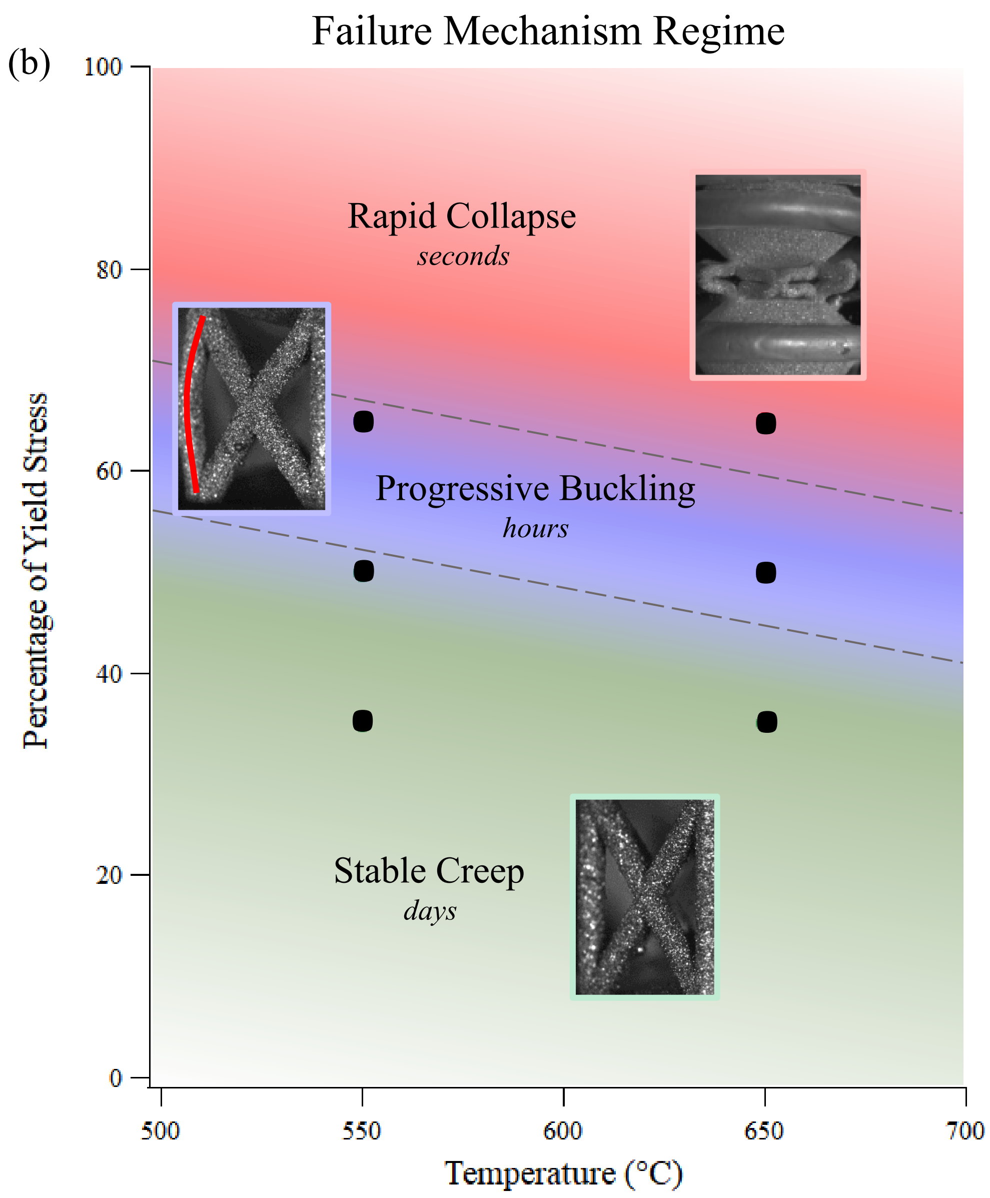
- Initial curvature found to be important parameter in creep buckling of a column (Hoff, Aeronaut. Quart., 1956)
- Buckling occurs in Z struts and diagonal struts
- Time delayed progressive buckling due to symmetry of specimen
- With sufficient bending outside of column changes from compression to tension



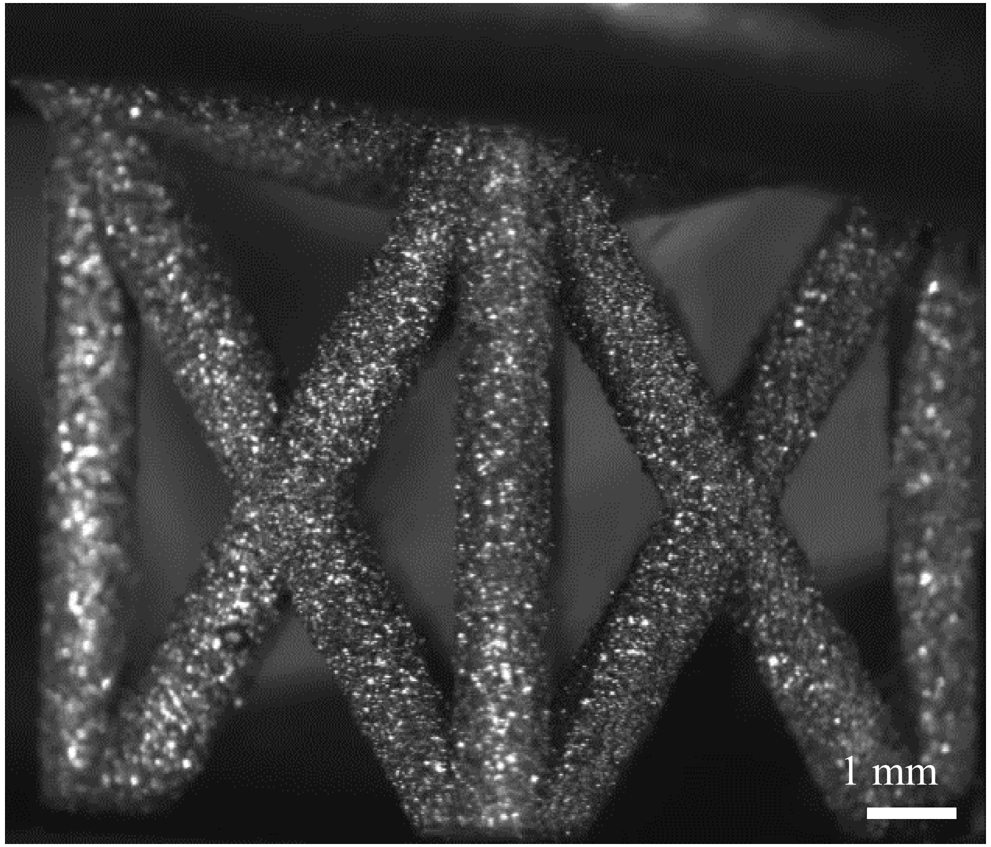

## Collapsed Lattices

- The radius of curvature is proportional to the creep curve
- Buckling of the struts is driving the compressive “creep” of the lattice
- Larger initial load caused larger initial bend (smaller radius of curvature)
- Higher temperature led to faster rupture time


(a)
Lattice Creep
Compressive Strain
Time (hours)
0.1
0.01
0.001
0.0001
0
5
10
15
20
25
2.8 Hrs
1 Min
25 hrs
150+
hours
550°C - low stress
550°C - medium stress
550°C - high stress
650°C - low stress
650°C - medium stress
650°C - high stress


(b)
Failure Mechanism Regime
Percentage of Yield Stress
Temperature (°C)
100
80
60
40
20
0
500
550
600
650
700
Rapid Collapse
seconds
Progressive Buckling
hours
Stable Creep
days

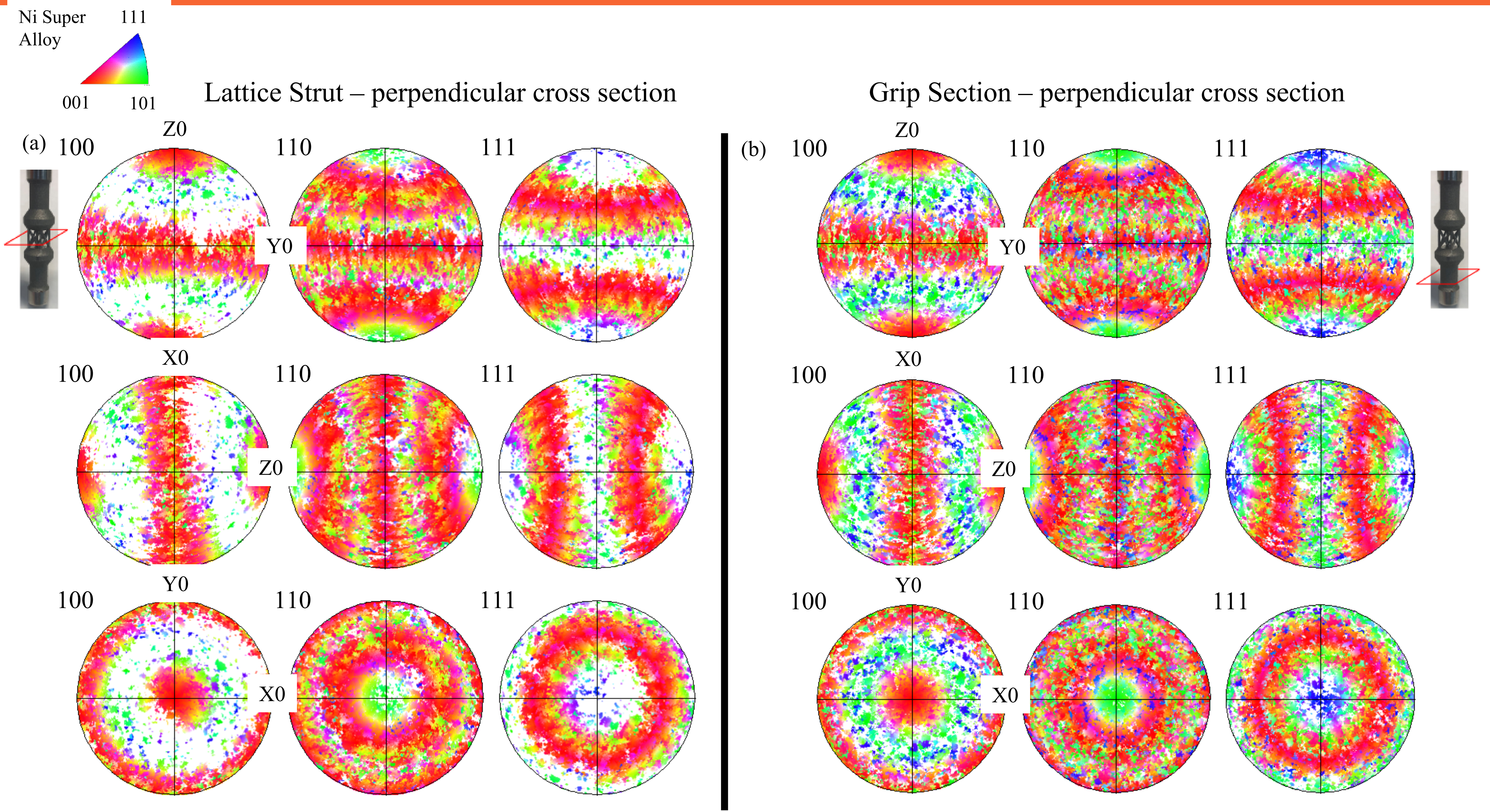
550 °C 65% of yield



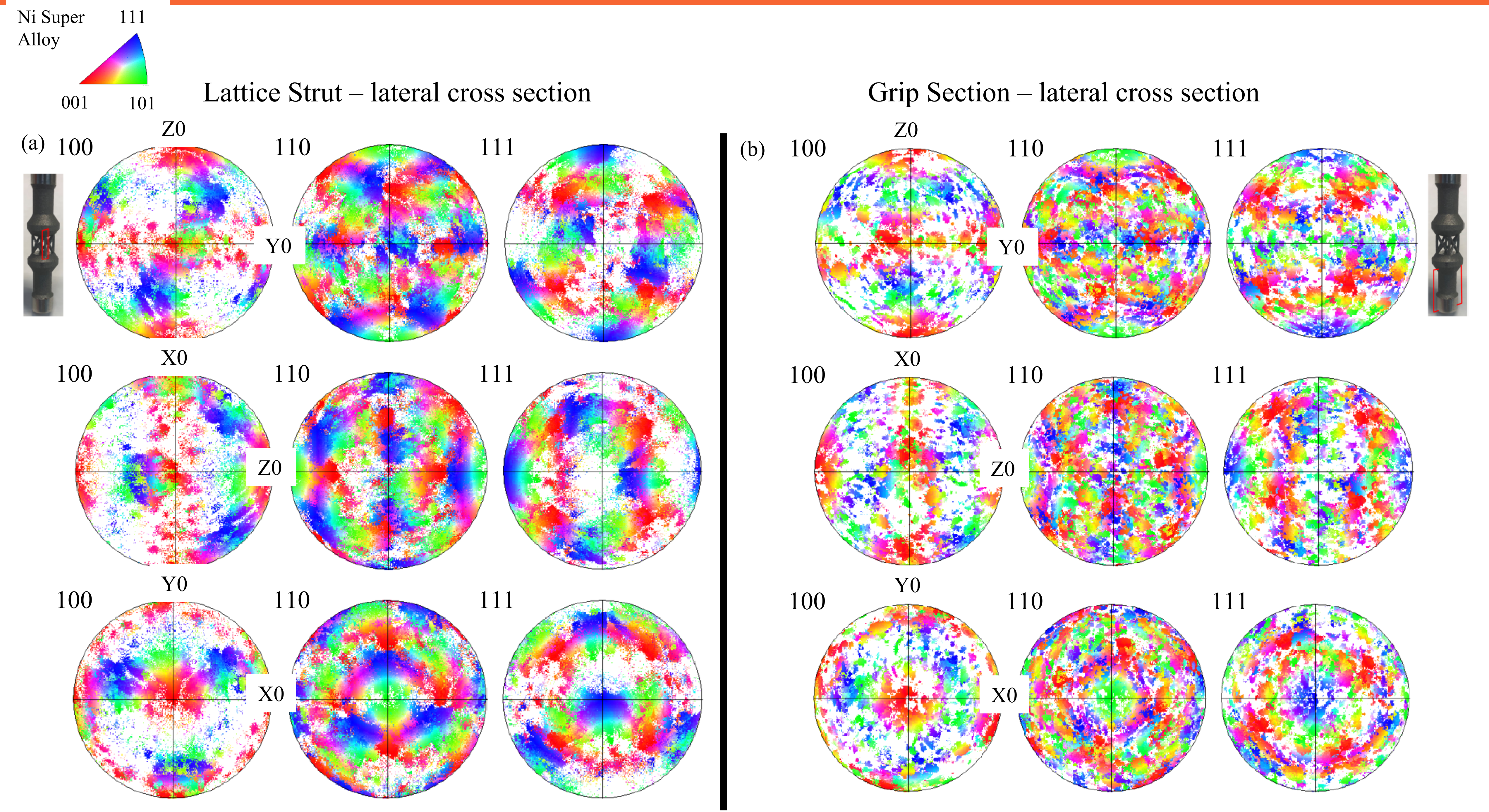

## Conclusions

- Buckling of struts drive creep deformation of FCCZ lattices
- FCCZ lattice more dependent on changes in stress and temperature than solid specimen
- Two orders of magnitude difference in steady state creep exponent
- Three identified failure mechanism regimes

# Extra or Hidden Slides

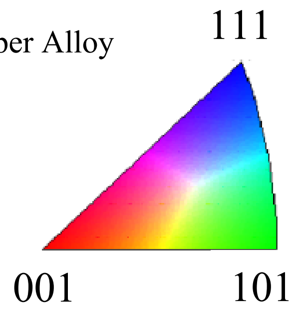


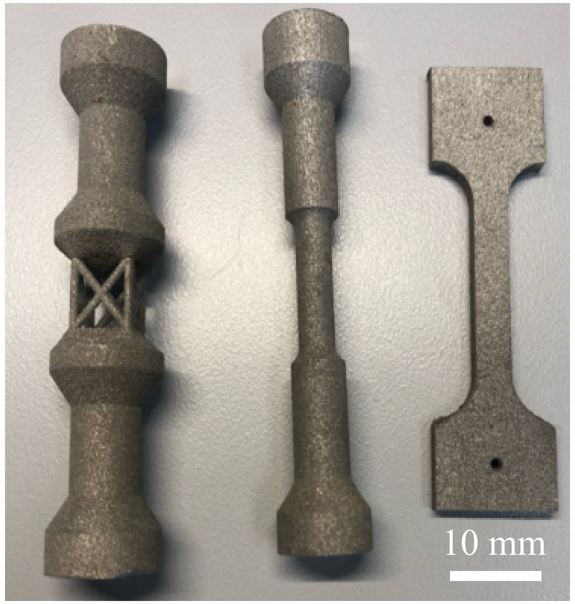
Ni Super Alloy
111
001
101
Lattice Strut – perpendicular cross section
Grip Section – perpendicular cross section
(a)
(b)
100
110
111
Z0
Y0
X0


Ni Super Alloy
111
001
101
Lattice Strut – lateral cross section
Grip Section – lateral cross section
(a)
100
Z0
110
111
Y0
100
X0
110
111
Z0
100
Y0
110
111
X0
(b)
100
Z0
110
111
Y0
100
X0
110
111
Z0
100
Y0
110
111
X0

# Material – AM Inconel 625

Ni Super Alloy

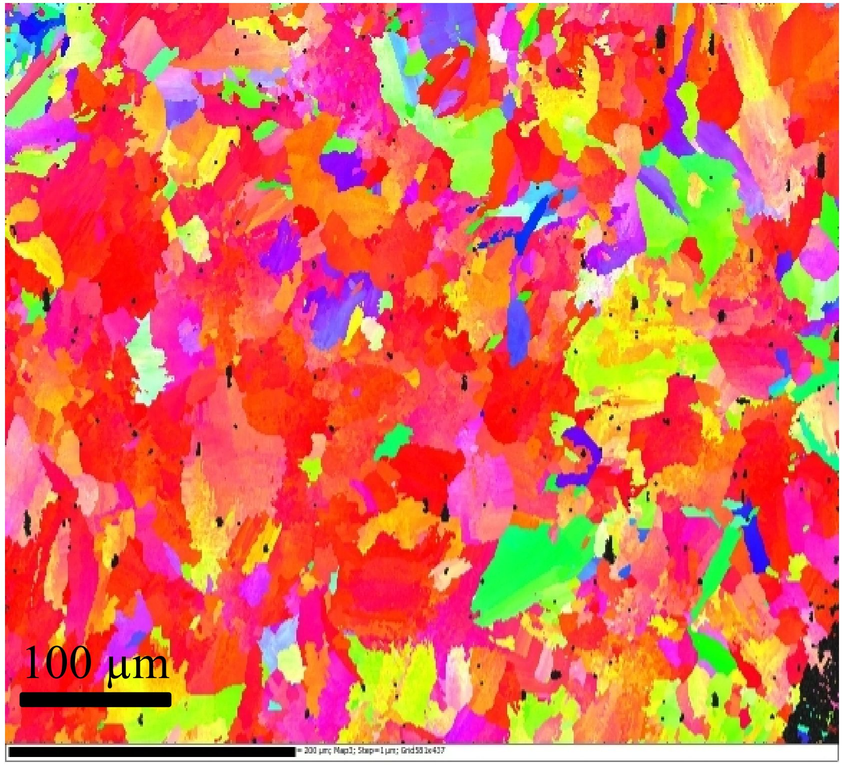



Laser Powder Bed AM
Power: 285 W
Speed: 960 mm/s

Beam ~80 µm diameter
Layer Height: 40 µm

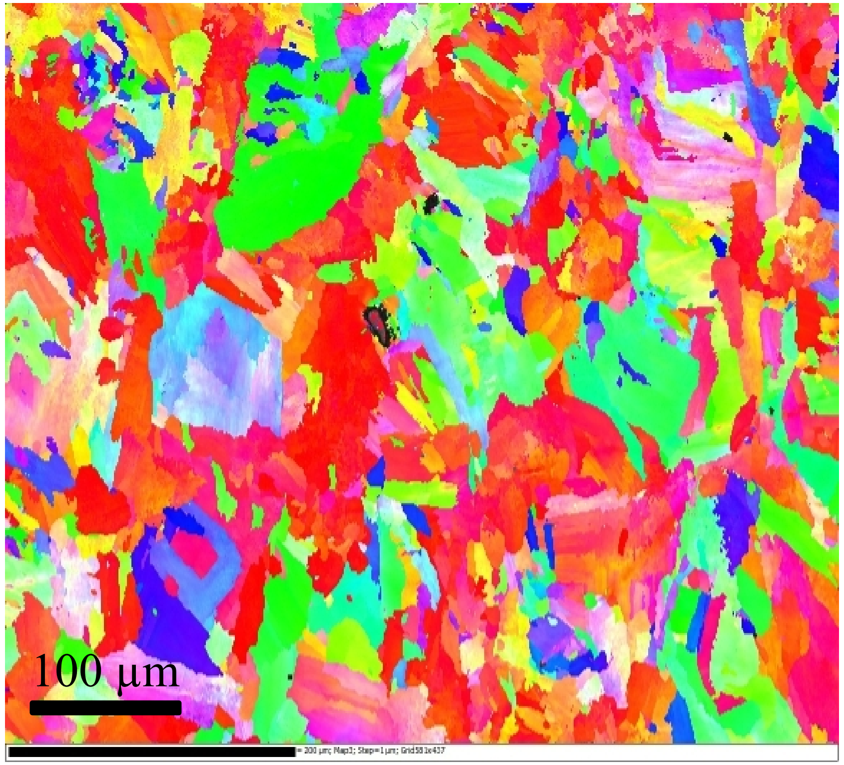
## Lattice Strut EBSD




Average Grain Area: 615 $\mu m^2$
Median Grain Area: 217 $\mu m^2$

Maximum Grain Size: 97.3 µm

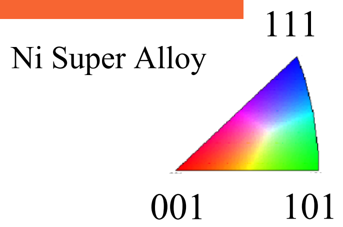
## Grip Section EBSD



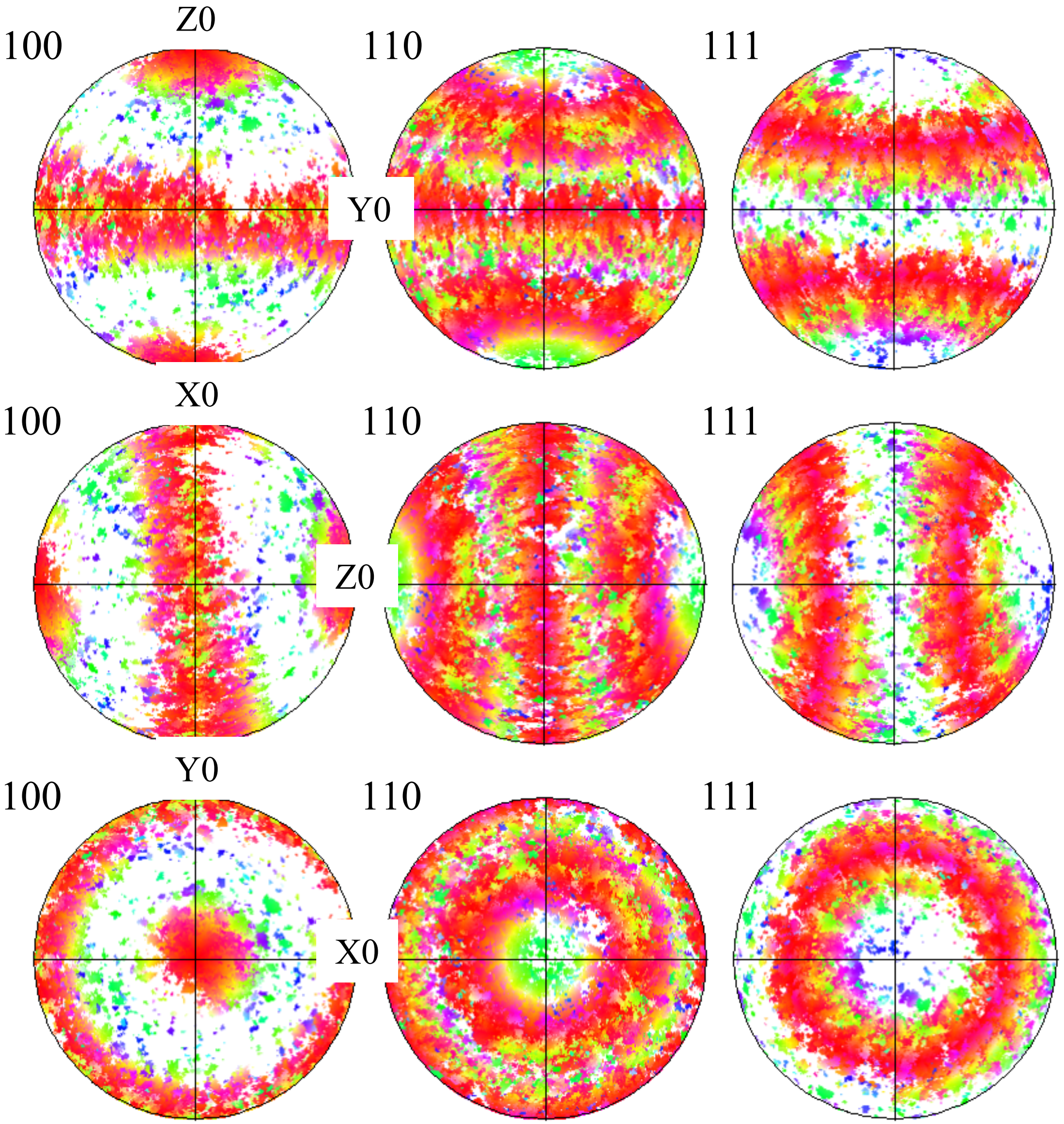

Average Grain Area: 444 $\mu m^2$
Median Grain Area: 150 $\mu m^2$

Maximum Grain Size: 89.6 µm

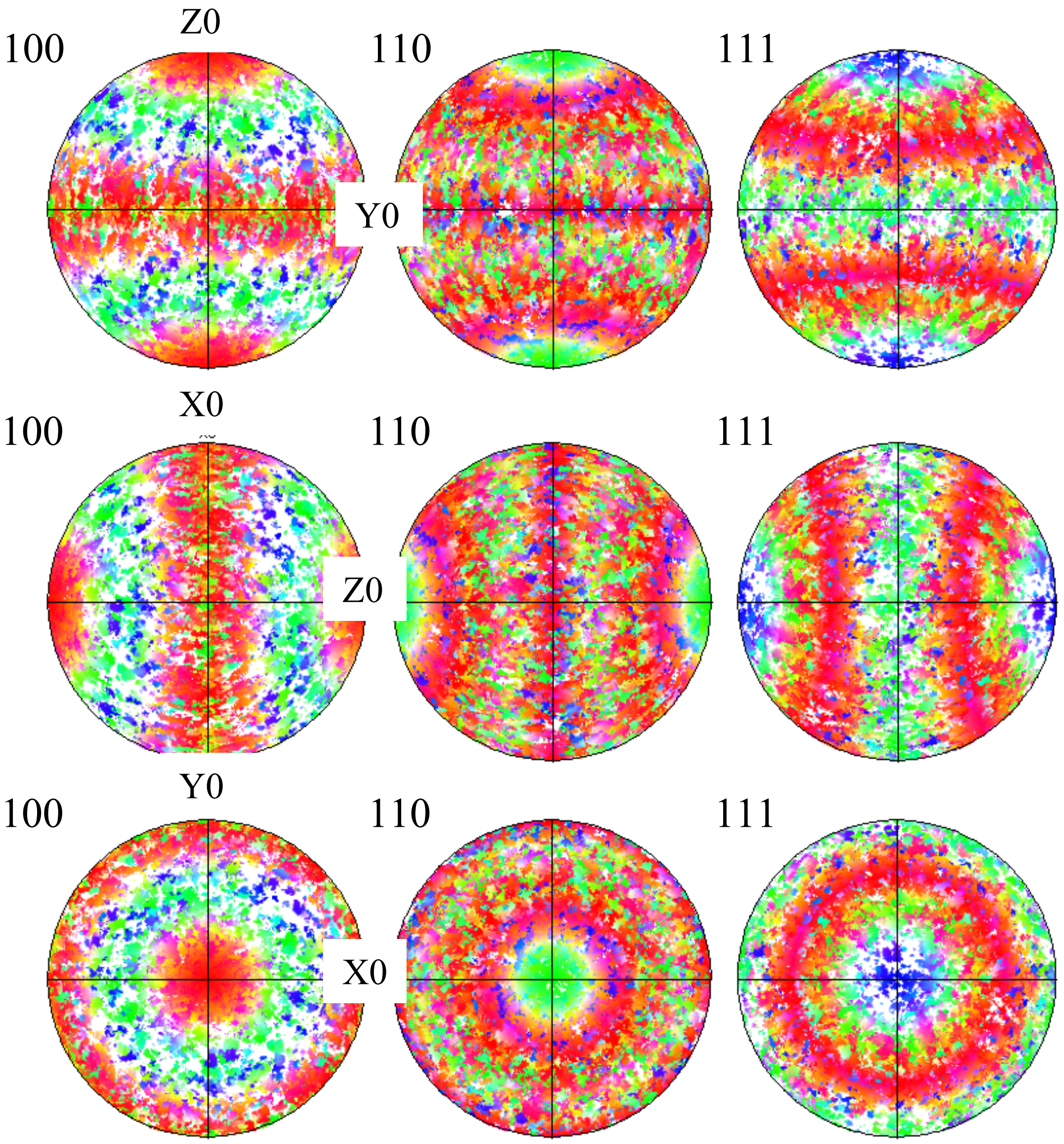
# Material – AM Inconel 625




## Lattice Strut EBSD



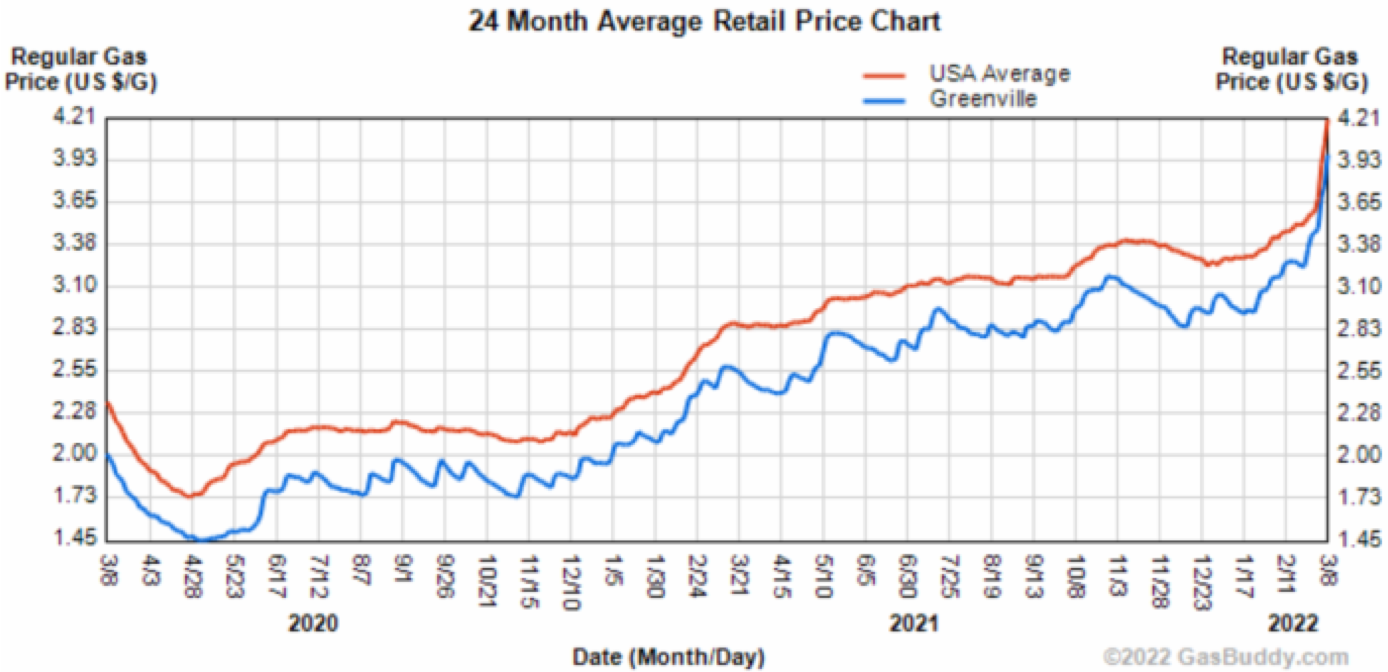

## Grip Section EBSD



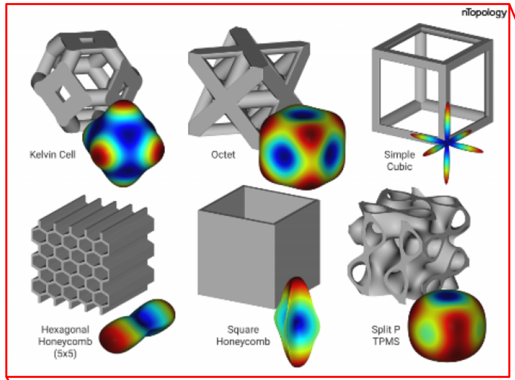
# Decreasing Weight and Waste

- Americans traveled 3.3 trillion vehicle miles in 2019, at $3/gallon ~$400 billion/year
- Reducing each vehicle by 0.5% save 528 million gallons/year
- Similar payoff for electric vehicles and battery life
- Lighter transportation means larger payloads and less fuel consumption

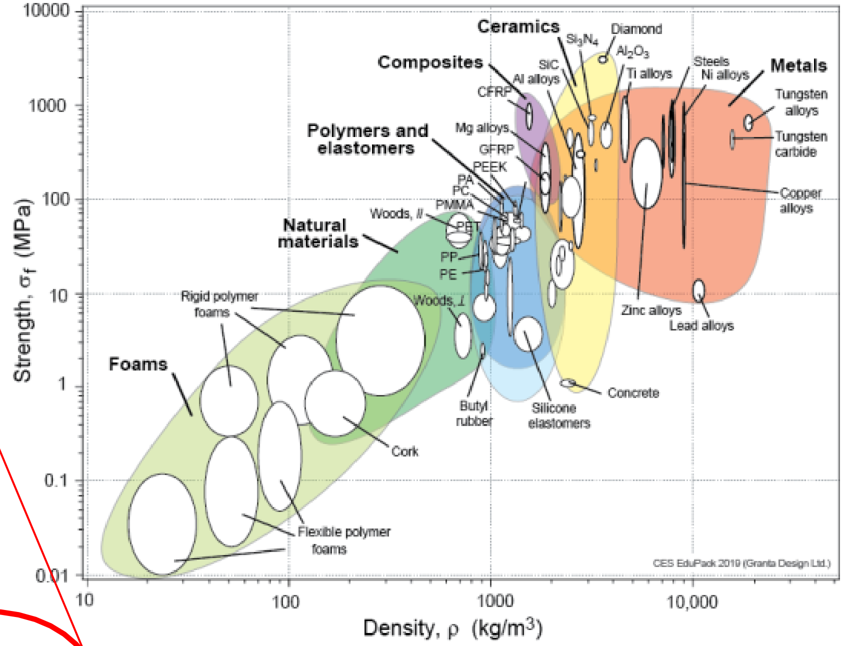

Toyota Camry



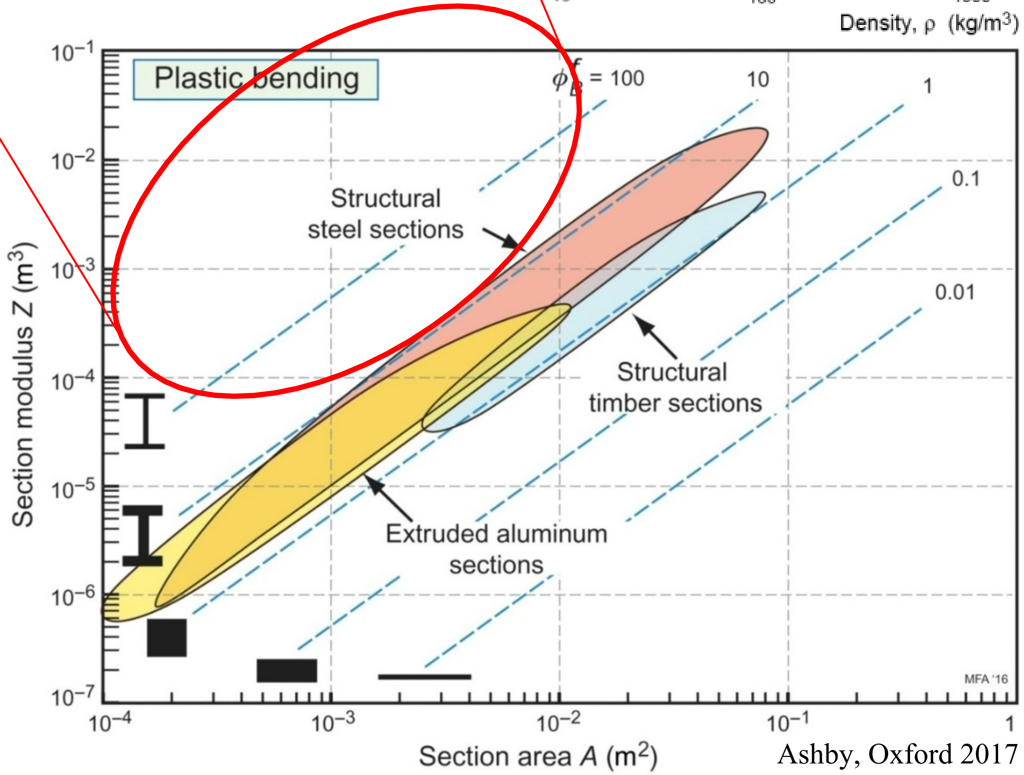

# Populating Material Space




Harris, nTopology 2020

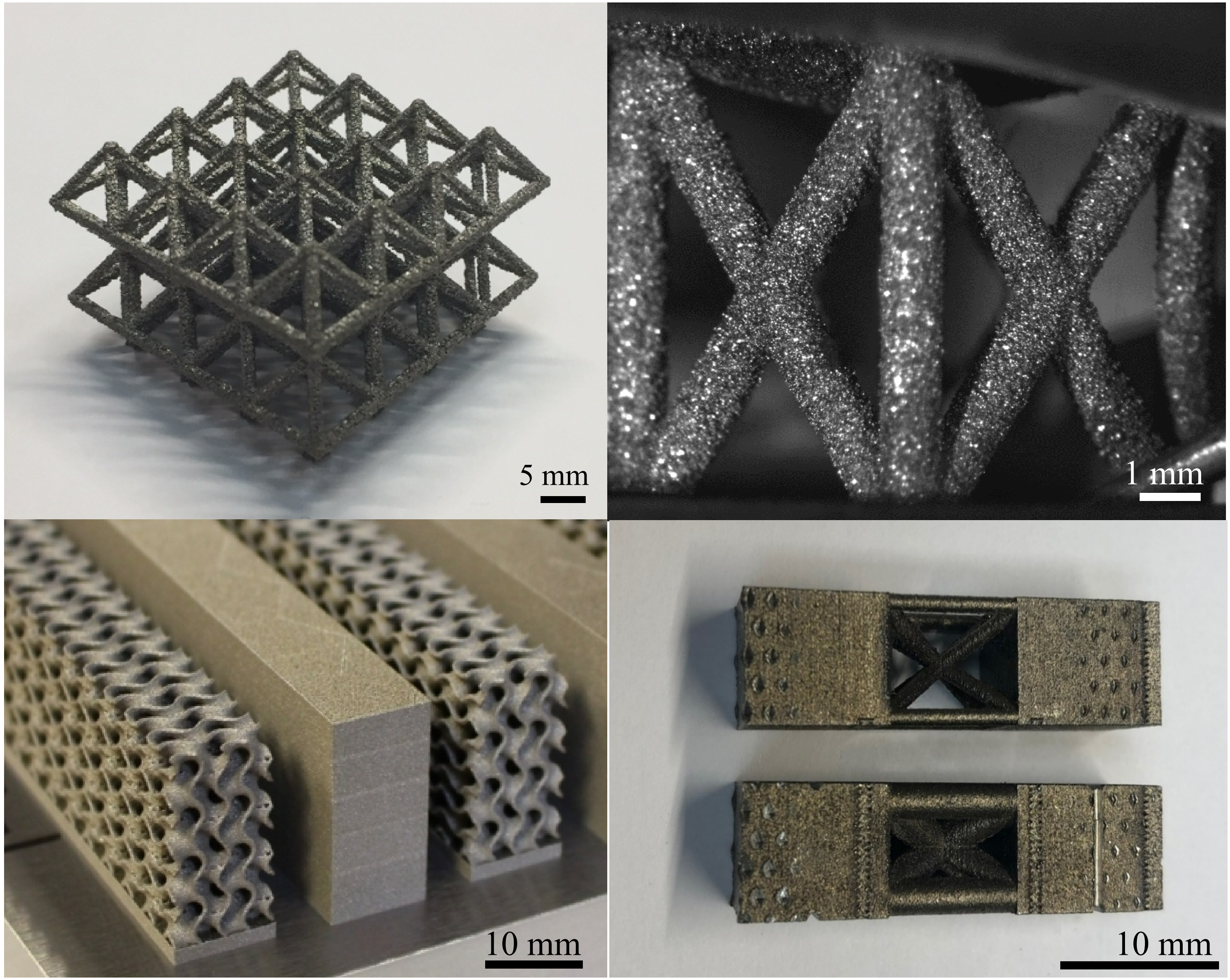



- Low density metamaterials use shape to achieve desired properties
- Populating empty design space
- Metamaterials use limited by lack of understanding of fracture and failure behavior
- Most metamaterial studies focused on elastic properties




Ashby, Oxford 2017

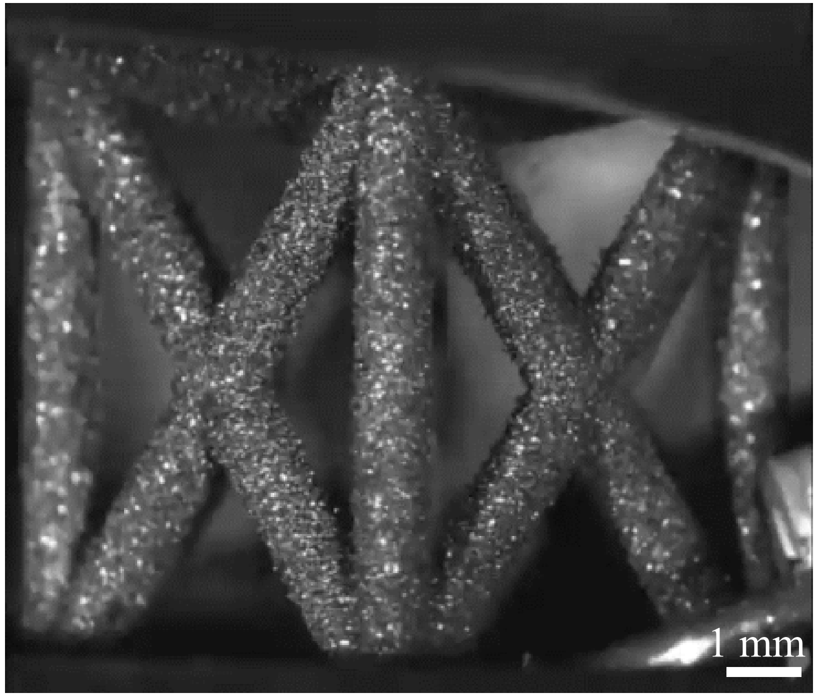
# Low Density Metamaterials at Elevated Temperatures




- More optimized strength-to-weight than foams
- Targeted material properties
- Topology selected to optimize multiple properties

# Compressive Creep Behavior of Low Density Metamaterials

650 °C 50% of yield




Creep of Inconel 625 FCCZ Lattices

Hypotheses

1) The lattice will have the same activation energy and steady state creep exponent as the bulk material when normalized for density – FALSE

2) The buckling of the Z-struts drives lattice failure – MOSTLY TRUE