Oregon State
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Practical Challenges and Failure Modes During Fabrication of Haynes 230 Micro-Pin Solar Receivers for High Temperature sCO_2 Operation

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3rd European Supercritical CO_2 Conference
Paper # 2019-sCO2.eu-157
September 19, 2019

COLLEGE OF
ENGINEERING

School of Mechanical, Industrial, and
Manufacturing Engineering

Outline

1. Concept and Methods
2. Failure Modes
3. Failure Mitigation
4. Conclusions

Concentrated Solar Thermal Power

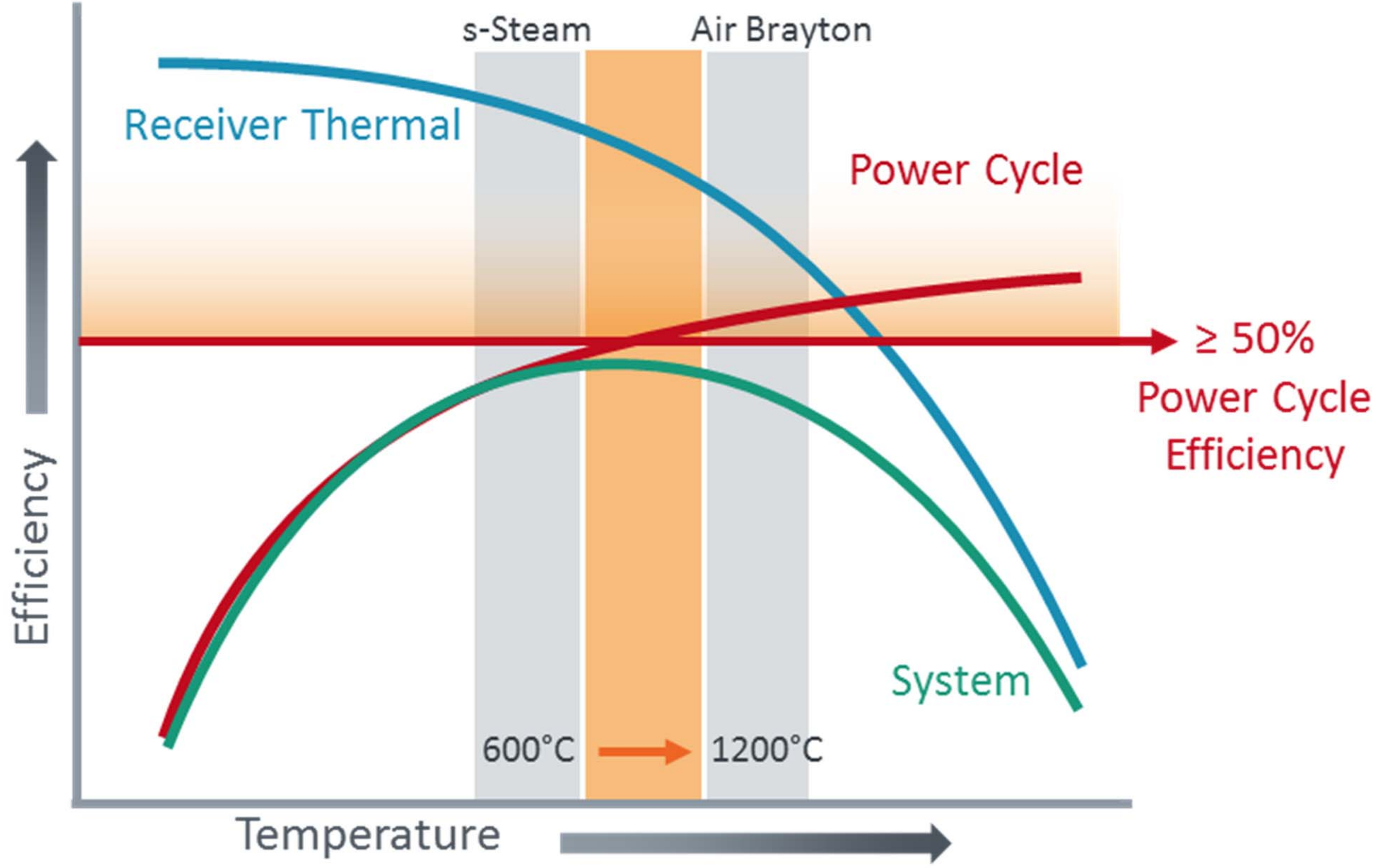
http://www.desertsun.com/story/tech/science/energy/2015/01/22/abengoa-big-plans-solar-towers-desert/22186683

Primary Challenge

$$\eta = 1 - \frac{T_C}{T_H}$$

$$q''_{loss} \propto T_s^4$$

Supercritical Brayton Cycle

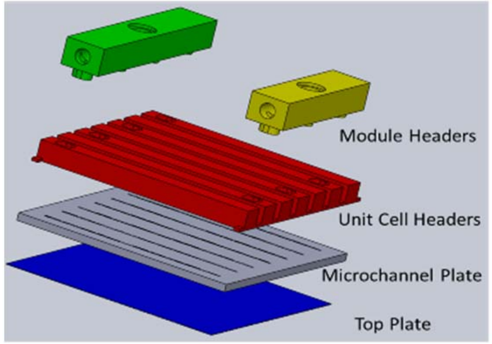


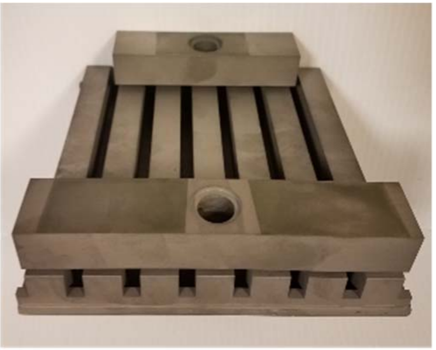
https://www.energy.gov/sites/prod/files/2018/02/f49/SETO%202018%20Portfolio%20Review%20-%20Day%201%20Keynote%20CSP_0.pptx

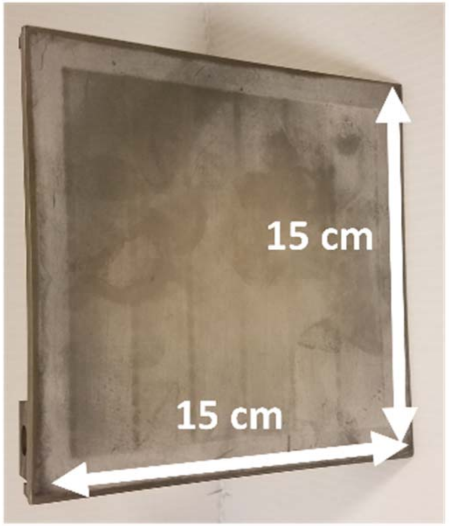
sCO$_2$ High Flux Receiver Development

Project Goals

- Receiver efficiency > 90%
- sCO$_2$ from 550°C to 720°C
- P = 250 bar
- < \$150/kW$_{th}$
- > 10,000 cycle life







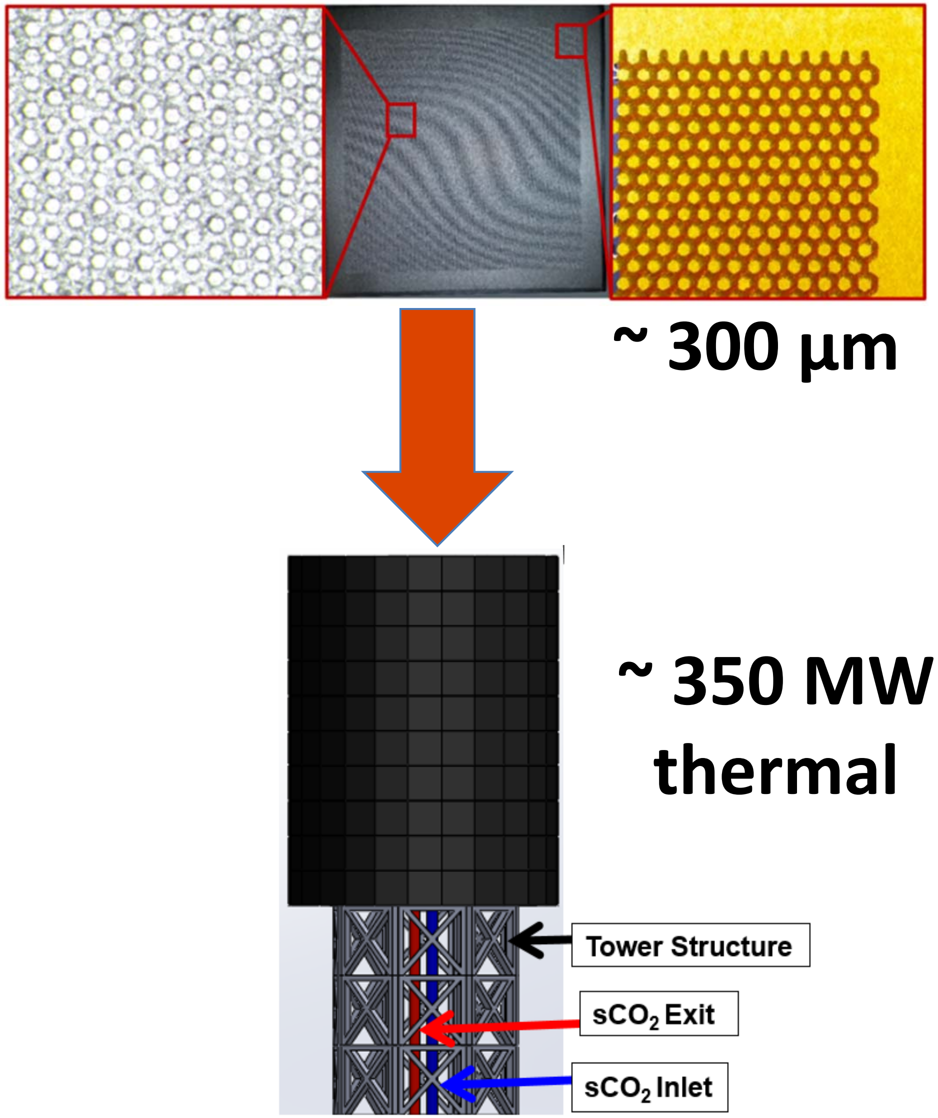
Micro-Pin Receiver Concept

Advantages

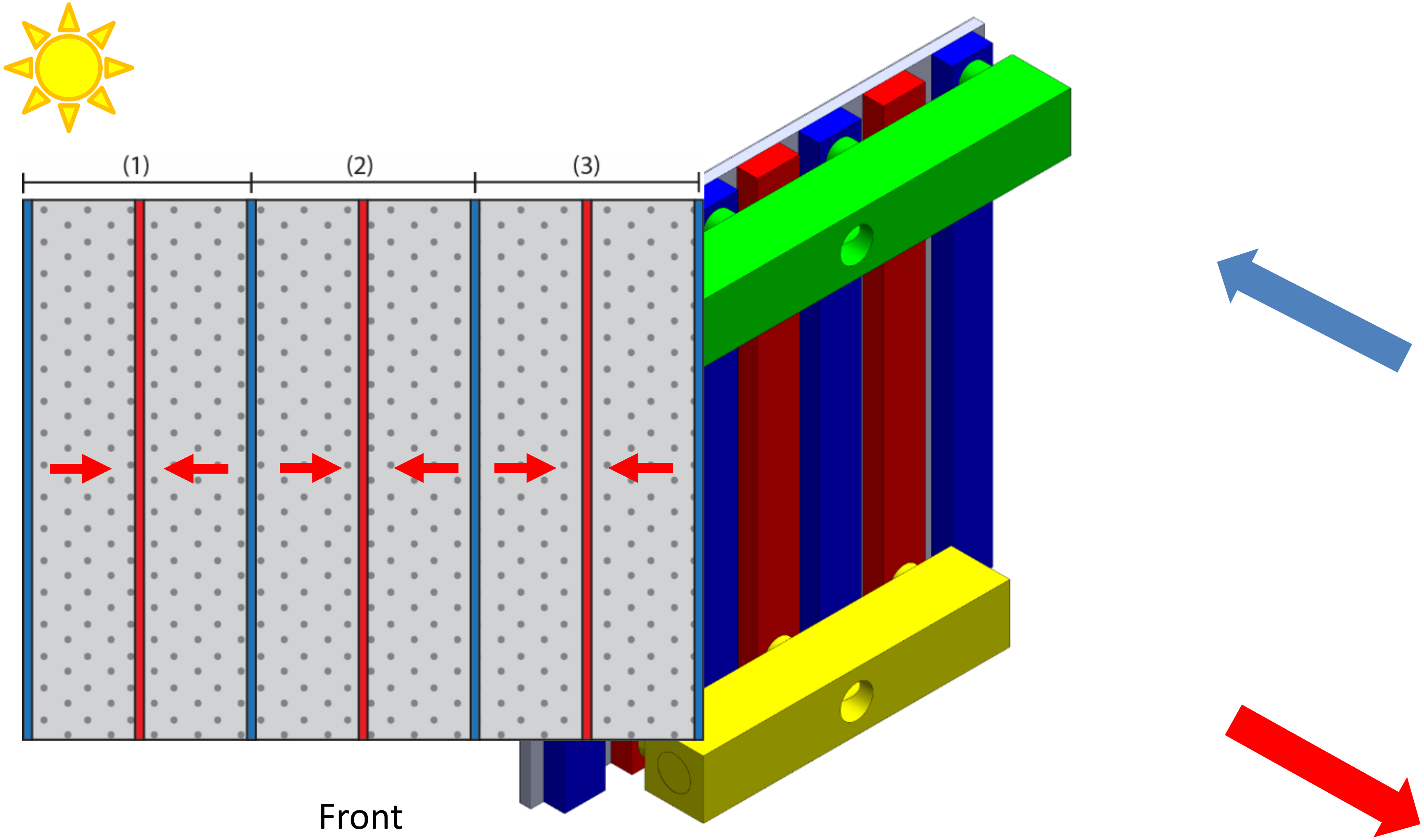
- D_H ↓ h ↑
- Thin walls
- Reduced material
- Modularity

Challenges

- Thermal hydraulic
- Manufacturing
- Reliability

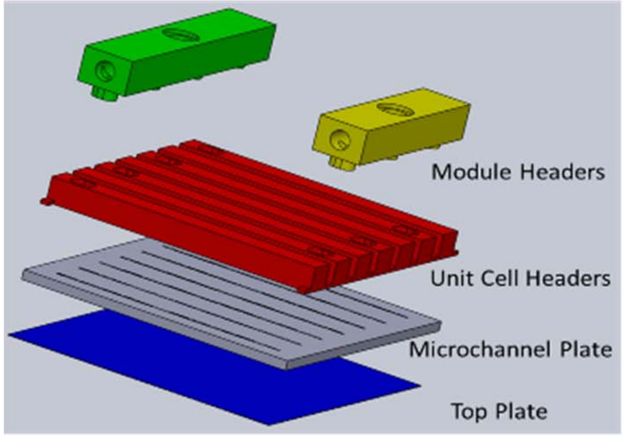


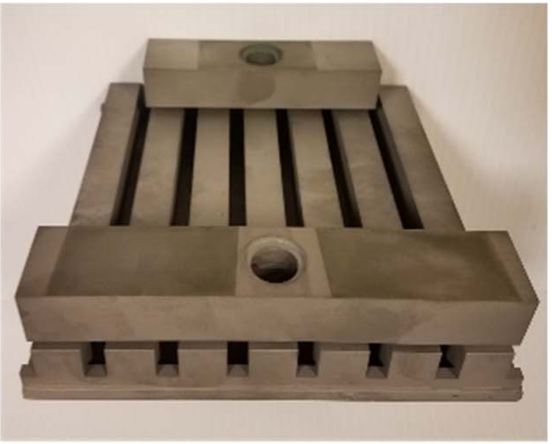
Module Design

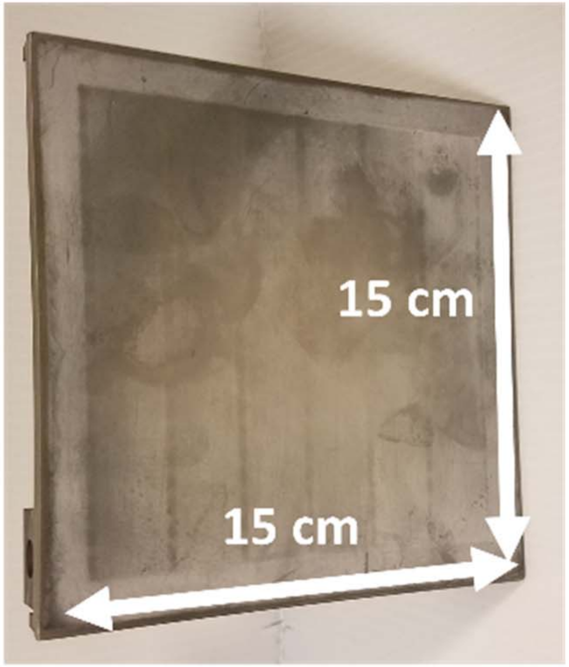


K.R. Zada, M.B. Hyder, M. Kevin Drost**, B.M. Fronk**, Numbering-up of microscale devices for megawatt-scale supercritical carbon dioxide concentrating solar power receivers, J. Sol. Energy Eng. 138 (2016) 61007. doi:10.1115/1.4034516.

Prototype Development







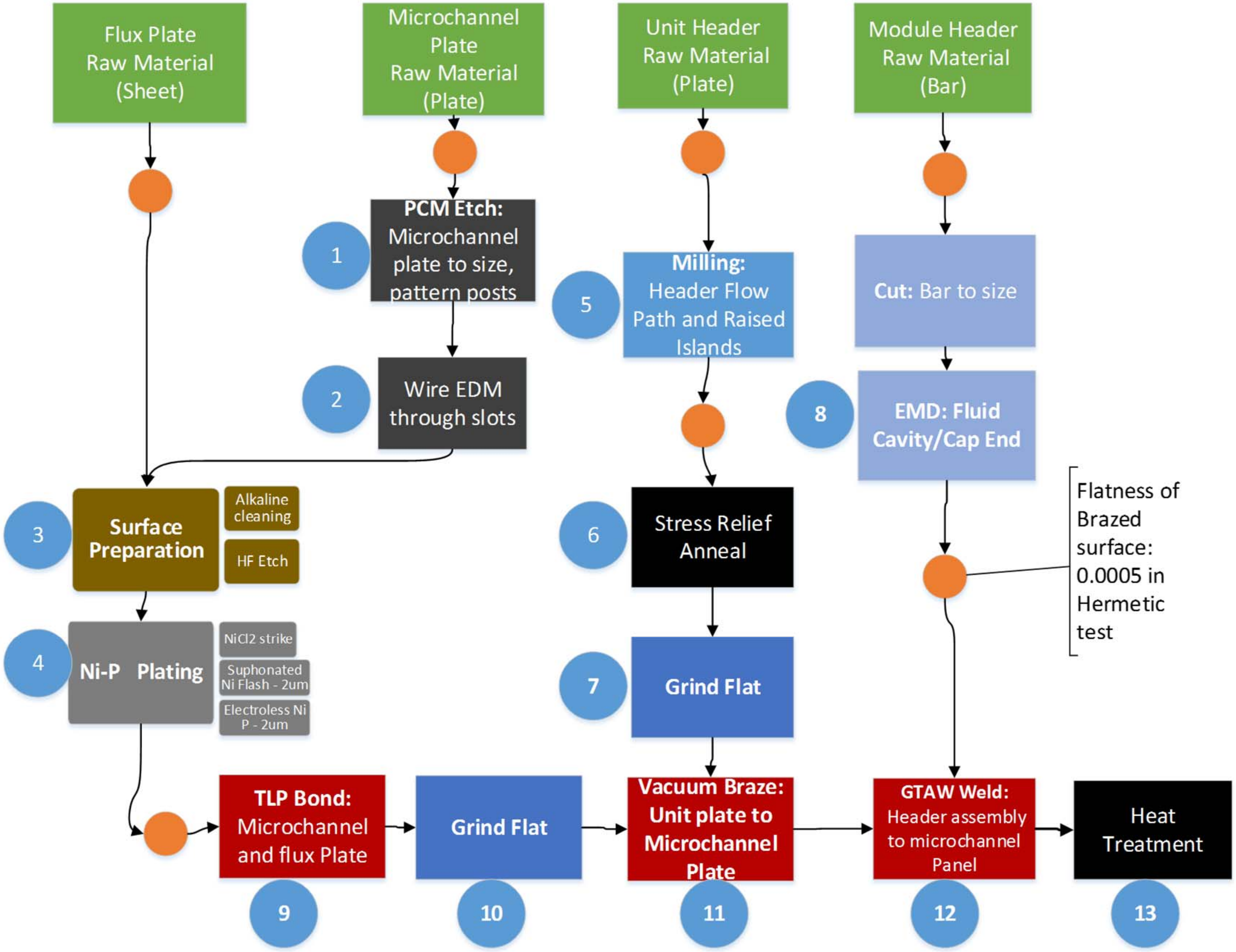
Material – Haynes 230

Component	Weight %
Nickel	57 (balance)
Chromium	22
Tungsten	14
Molybdenum	2
Iron	3 (max)
Cobalt	5 (max)
Manganese	0.5
Silicon	0.4
Niobium	0.5 (max)
Aluminum	0.3
Titanium	0.1 (max)
Carbon	0.1
Lanthanum	0.02
Boron	0.015 (max)

- Corrosion resistance
- Allowable stress at temperature
- Ability to TLP/diffusion bond
- Weldabiltiy
- Ability to photochemical etch
- Ability to procure in required form factors

https://www.haynesintl.com/docs/default-source/pdfs/new-alloy-brochures/high-temperature-alloys/brochures/230-brochure.pdf

Fabrication Method



Flux Plate Raw Material (Sheet)

Microchannel Plate Raw Material (Plate)

1 **PCM Etch:** Microchannel plate to size, pattern posts

2 Wire EDM through slots

3 **Surface Preparation**
- Alkaline cleaning
- HF Etch

4 **Ni-P Plating**
- NiCl2 strike
- Suphonated Ni Flash - 2um
- Electroless Ni P - 2um

Unit Header Raw Material (Plate)

5 **Milling:** Header Flow Path and Raised Islands

6 Stress Relief Anneal

7 **Grind Flat**

Module Header Raw Material (Bar)

Cut: Bar to size

8 **EMD: Fluid Cavity/Cap End**

Flatness of Brazed surface: 0.0005 in
Hermetic test

9 **TLP Bond:** Microchannel and flux Plate

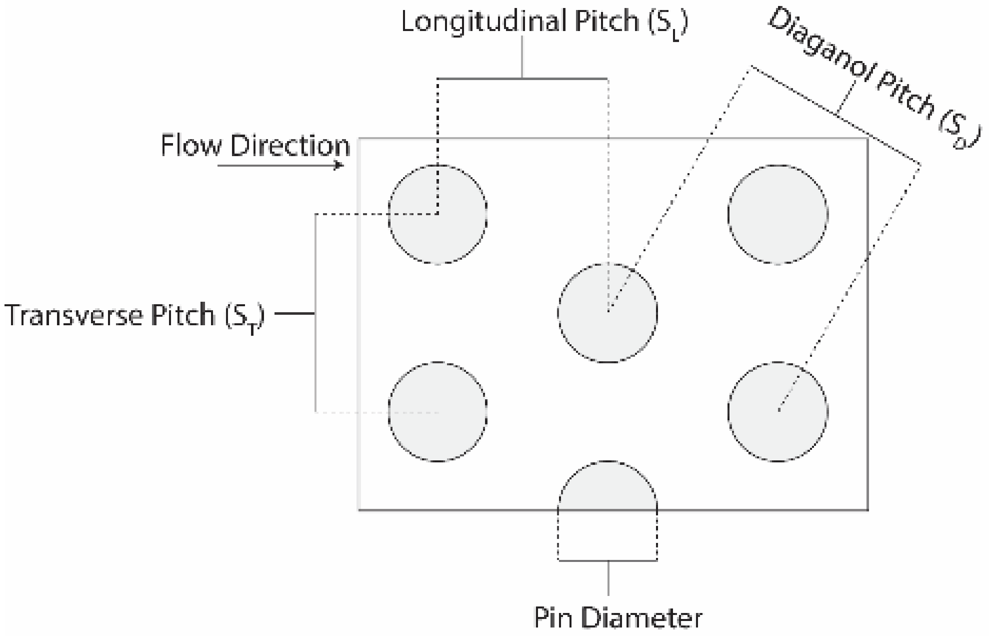
10 **Grind Flat**

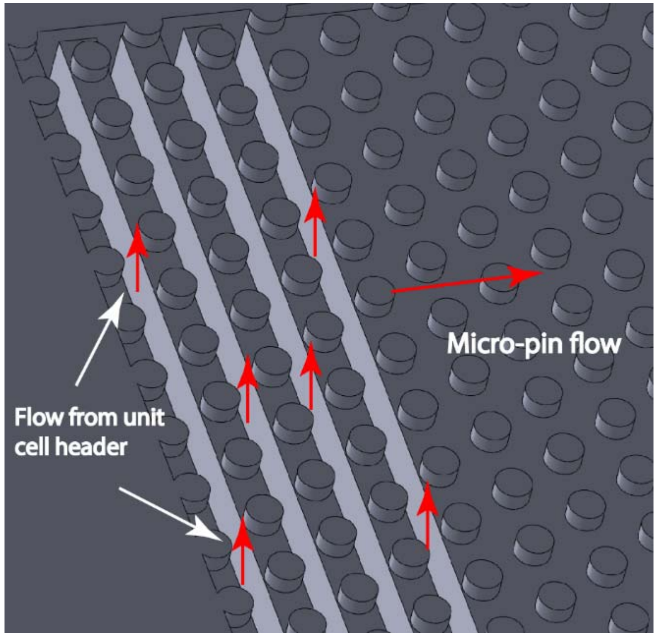
11 **Vacuum Braze: Unit plate to Microchannel Plate**

12 **GTAW Weld:** Header assembly to microchannel Panel

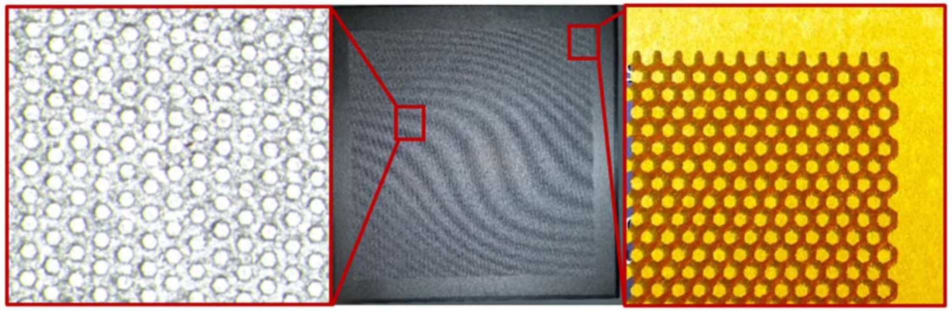
13 Heat Treatment

Fabrication Method – Pin Array

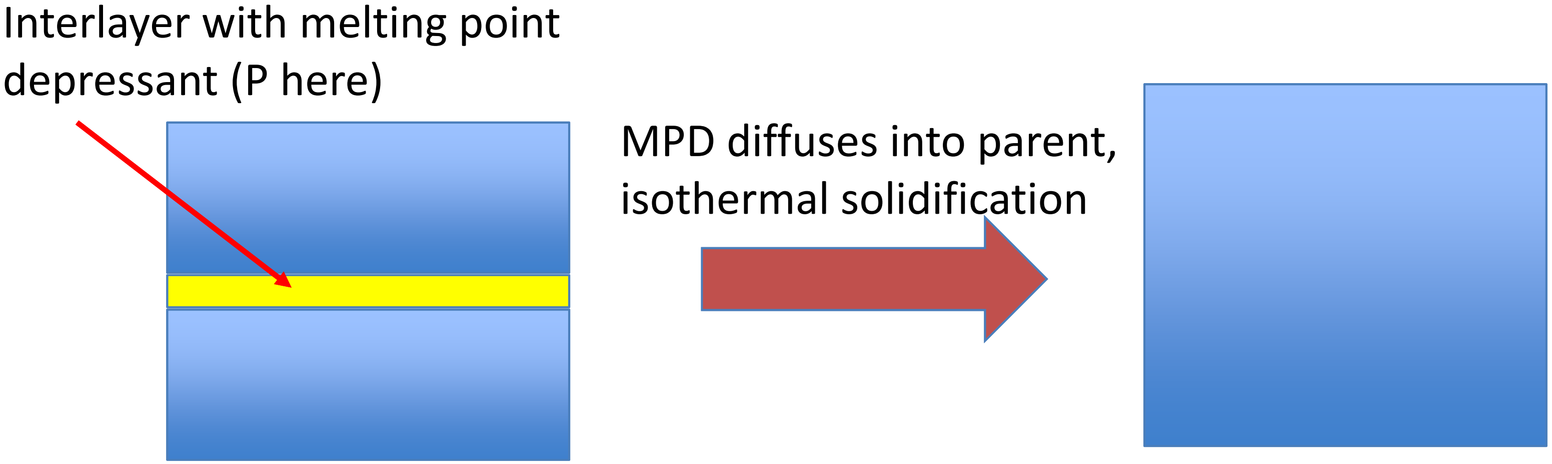




Variable Name	Dimension	Value
D_{pin}	Pin diameter	300 μm
h_{pin}	Pin height	150 μm
S_L	Longitudinal pitch	520 μm
S_T	Transverse pitch	600 μm
S_D	Diagonal pitch	600 μm



Fabrication Method – Transient Liquid Phase Bond

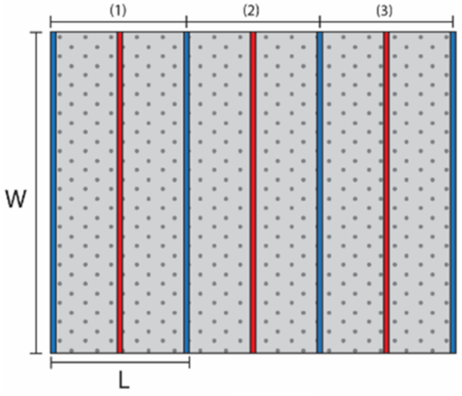


Interlayer with melting point depressant (P here)

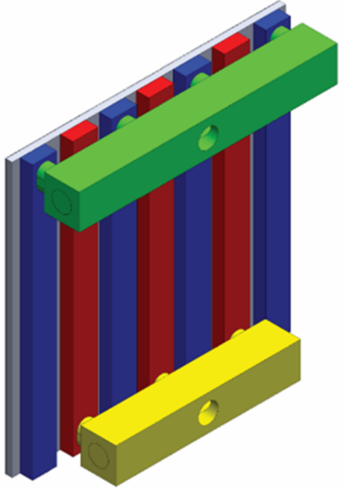
MPD diffuses into parent, isothermal solidification

- First NiCl strike was applied to help increase adhesion.
- Then, a 2 μm sulfonated layer of pure nickel was electrically deposited, followed by a 2 μm electroless mid-phosphorus layer (~6% P).
- This resulted in a phosphorous content of approximately 3% in the interlayer.
- The bonding temperature was 1150 °C at a vacuum pressure less than 1×10^{-5} torr for a dwell time of 4 hours.

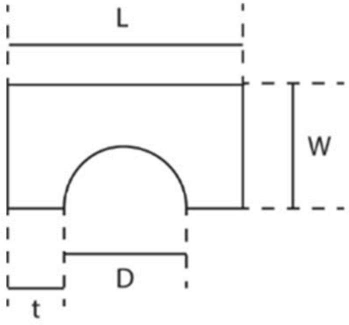
Fabrication Methods - Brazing



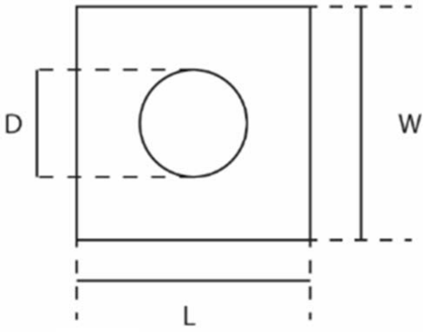
(A)



(B)



(C) Unit Cell Header

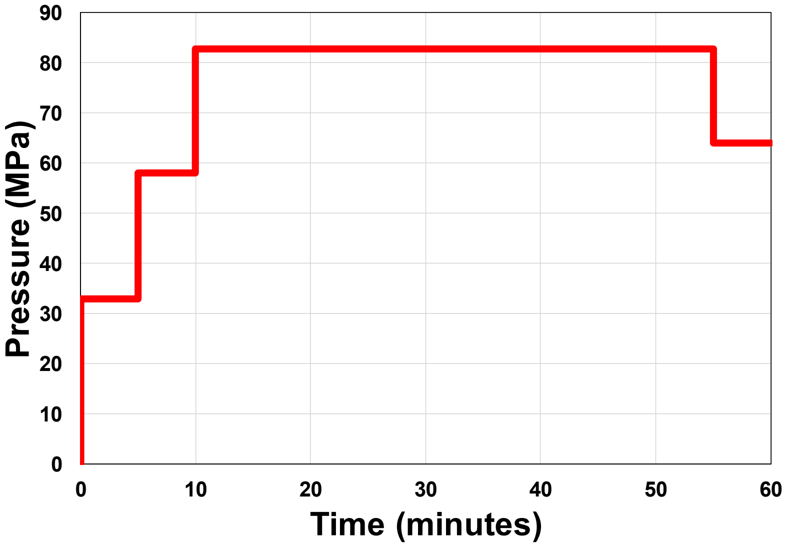


(D) Module Header

Step	Description
1	Ramp to 950 °C @ 5 °C per minute
2	1st Hold: 950 °C for 1.5 hours
3	2nd Hold: 1195 °C for 2.5 hours
4	Cool to 1100 °C (2 °C per min) in 1.5 mbar Argon
5	3rd Hold: 1100 °C for 3.5 hours

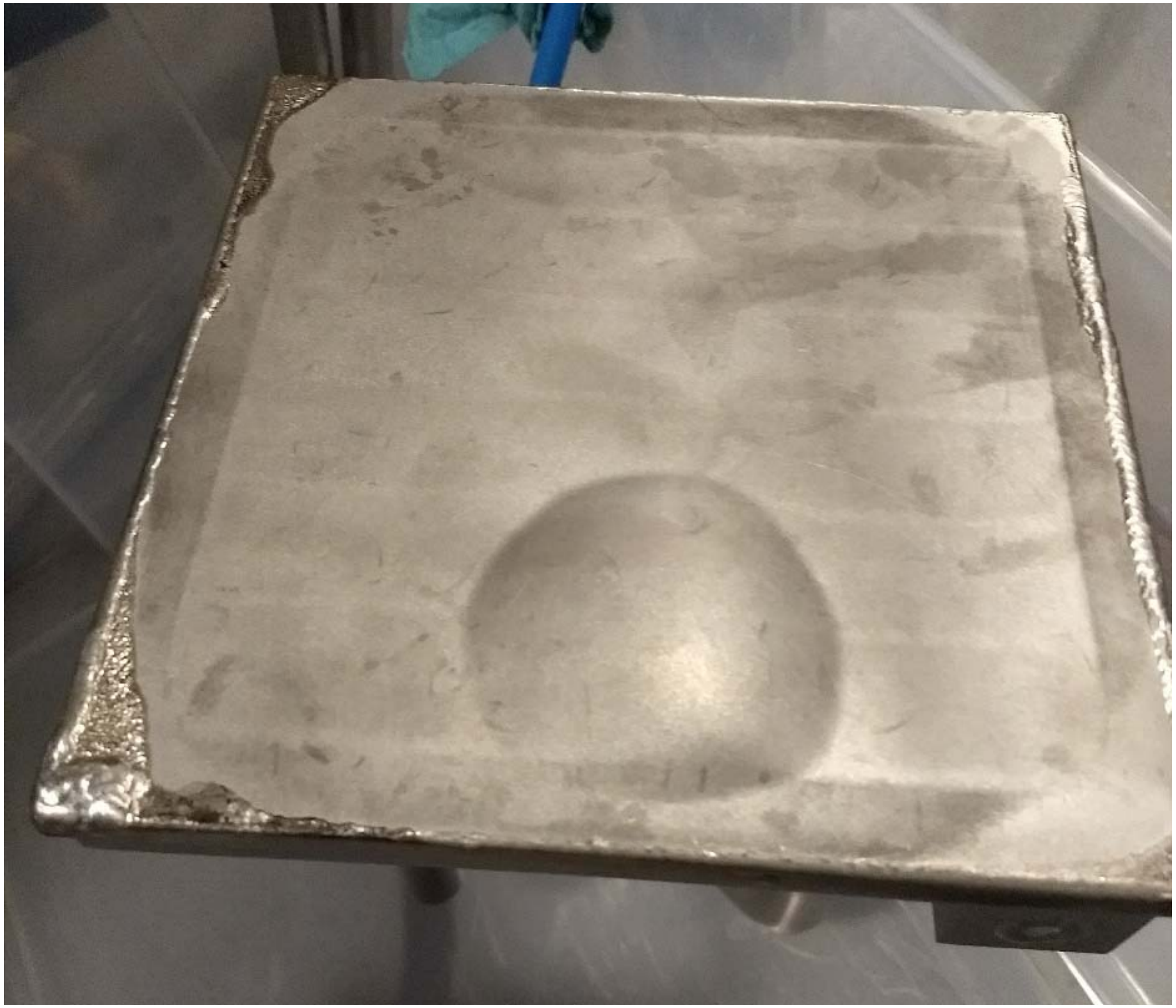
Header	W (mm)	L (mm)	D (mm)	t (mm)
(A) Unit-cell header	8.125	16.25	6.25	5
(B) Module header	22.7	22.7	12.7	5

Proof Pressure Test

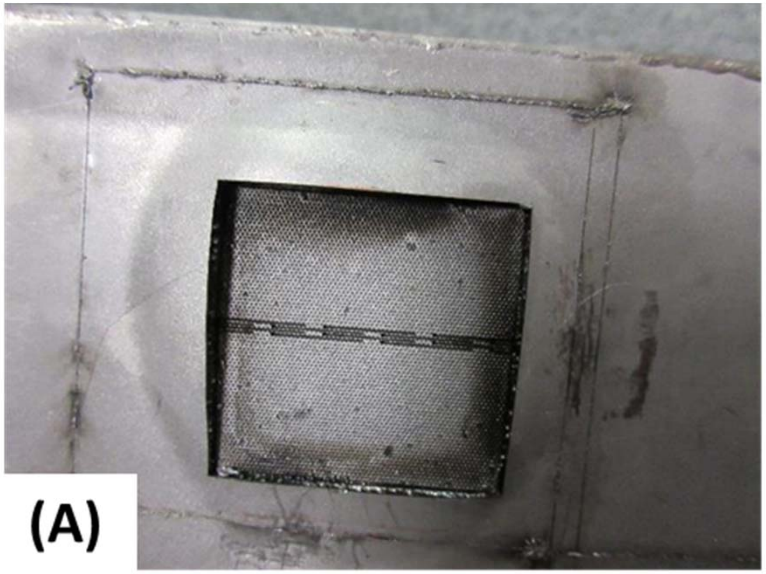


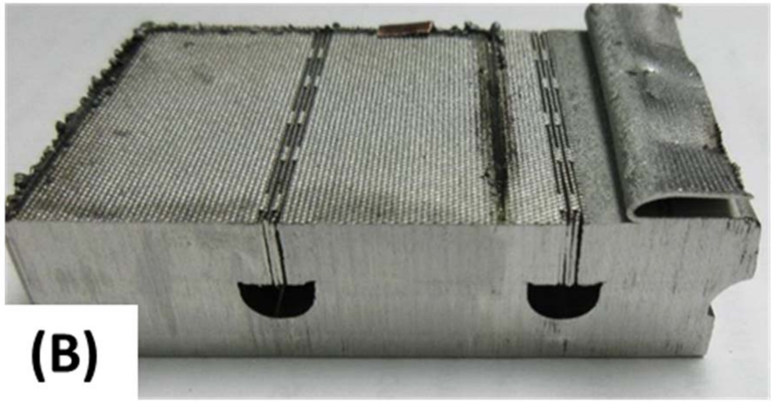
$$P = 1.3 \cdot MAWP \cdot \frac{\sigma_T}{\sigma_D}$$

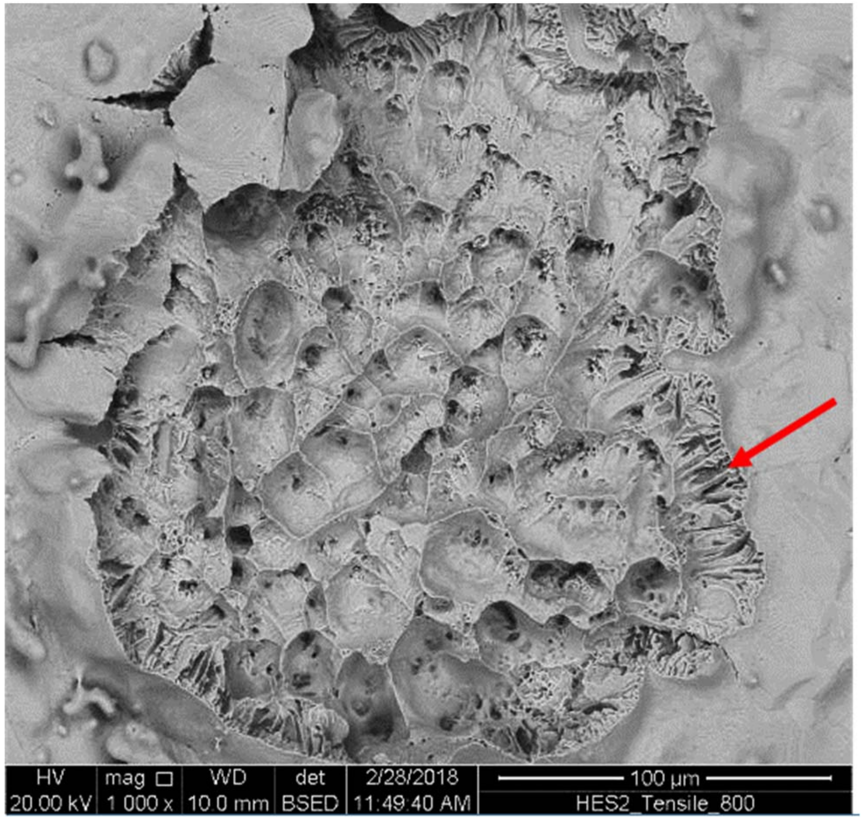
Failure Mode



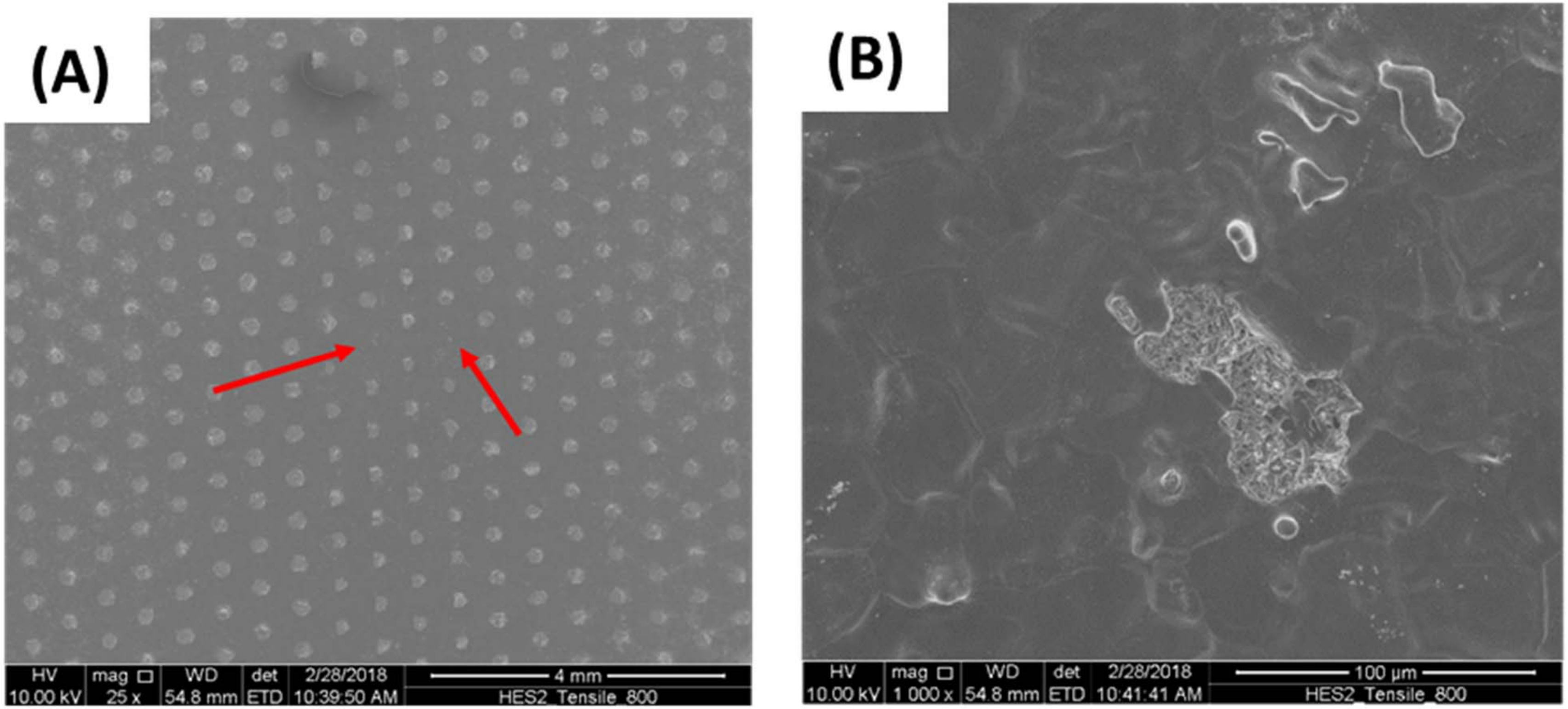
Failure Mode Analysis





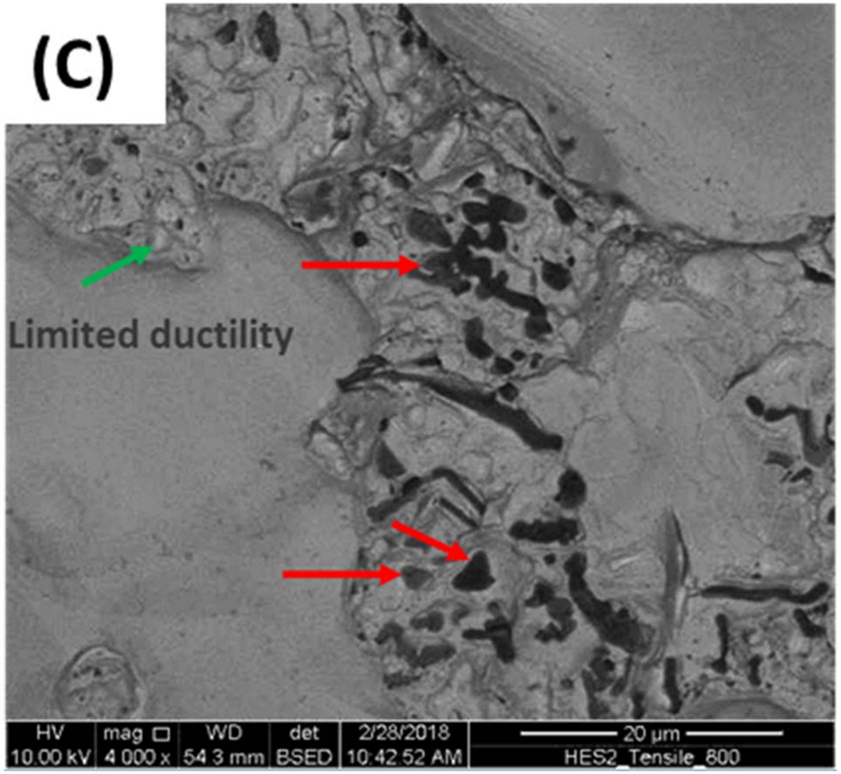


Failure Related to TLP



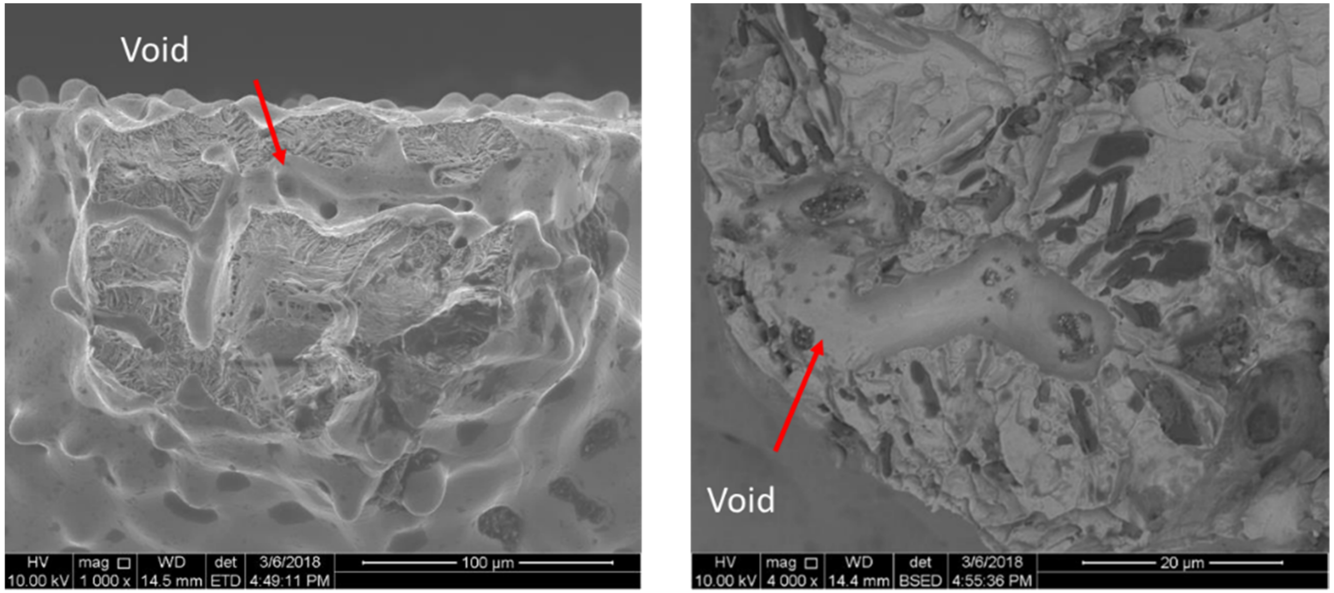
- Limited bonding in “missing pin”

Failure Related to TLP



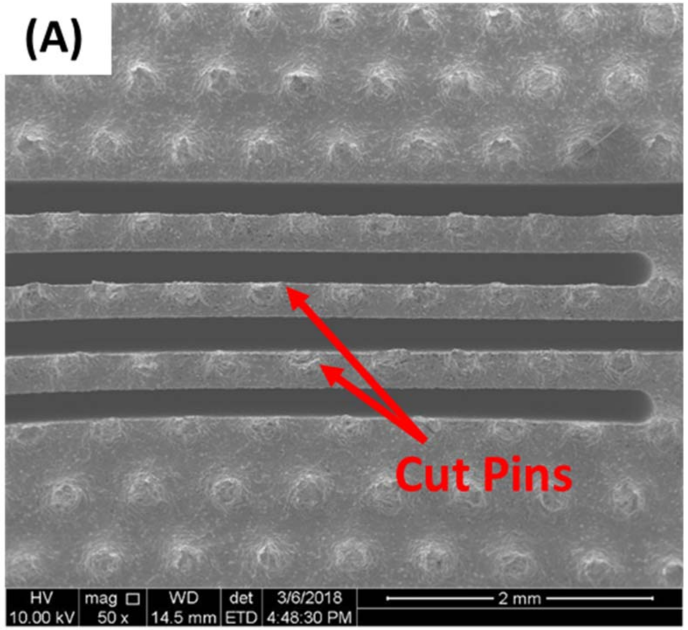
- Al-oxide in poorly bonded region
- Limited ductility in failure

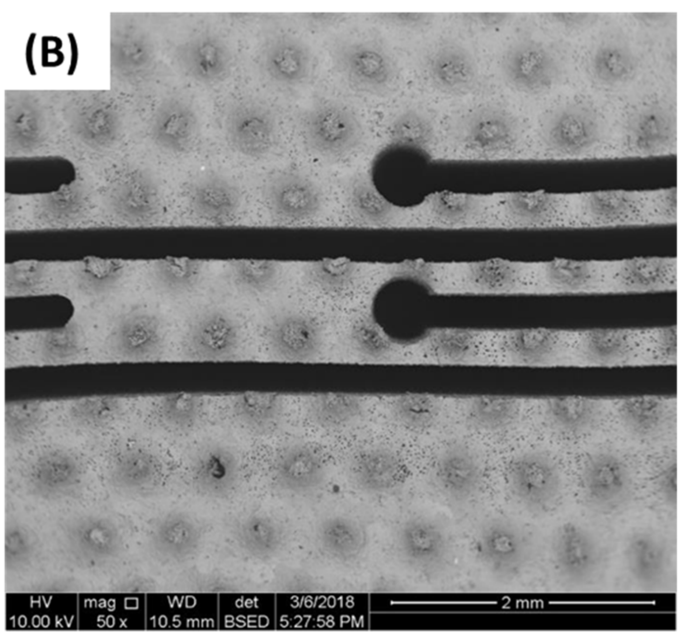
Failure Related to TLP



- Slow/uneven diffusion of Phosphorous could yield an incomplete bond
- Bond could re-liquefy during braze or heat treatment
  - Slippage
  - Voids
  - O_2 ingression easier
- **ACTION**: Faster diffusing MPD or solid diffusion bond

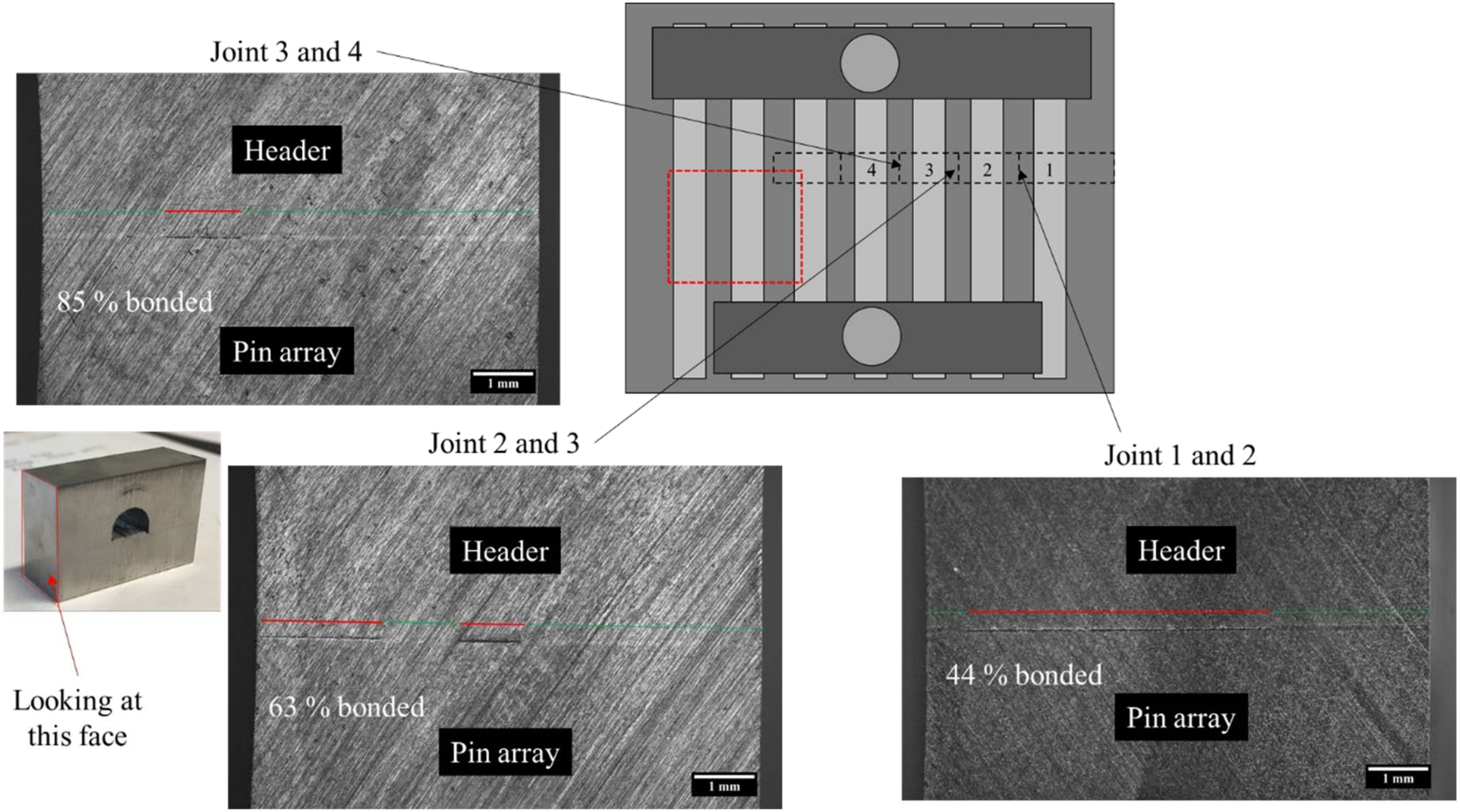
Failure Related to Design





- Inlet/outlet slit region sensitive to manufacturing defects
- Pin array ideal for HT and ΔP, but not robust.

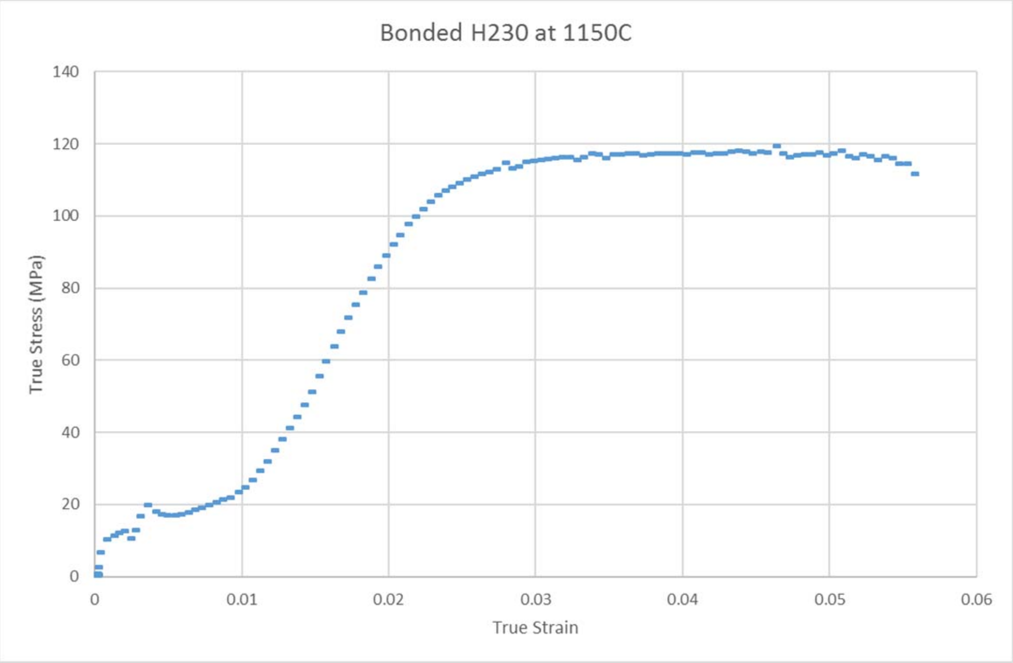
Failure Related to Braze



Failure Mode Mitigation

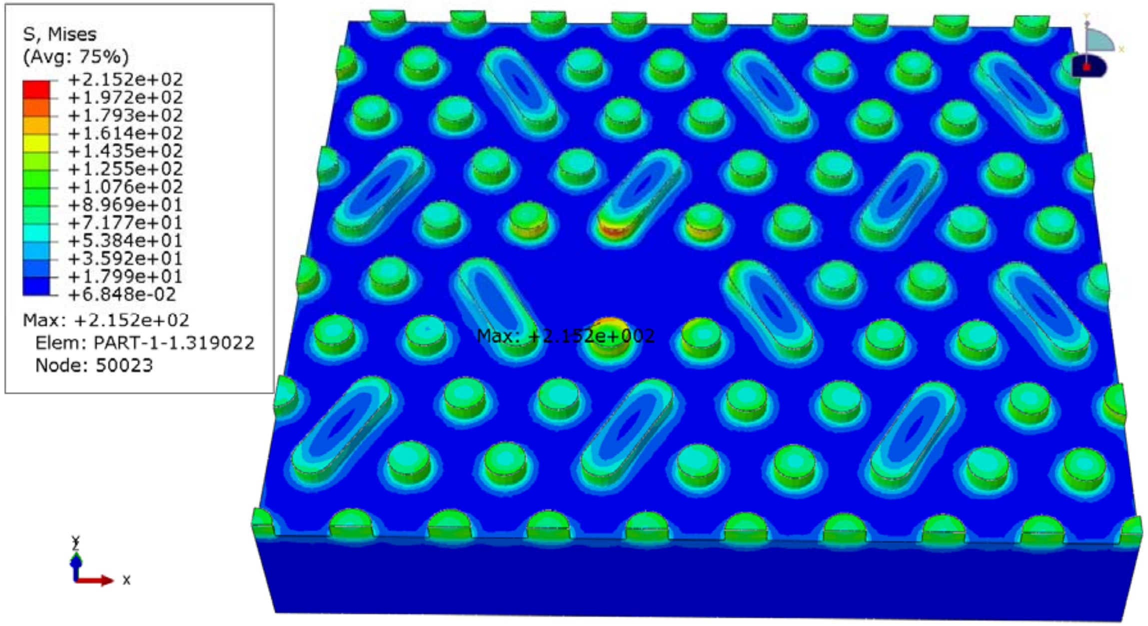
Failure Mode Identifier	Description
A	Liquification w/o bonding pressure (unbonded and poorly bonded pins)
B	Aluminum oxide formation
C	Voids
D	Cut pins due to wire EDM
E	Carbon contamination due to wire EDM
F	Insufficient safety factor for “missing” pins
G	Insufficient bonding pressure in slit region

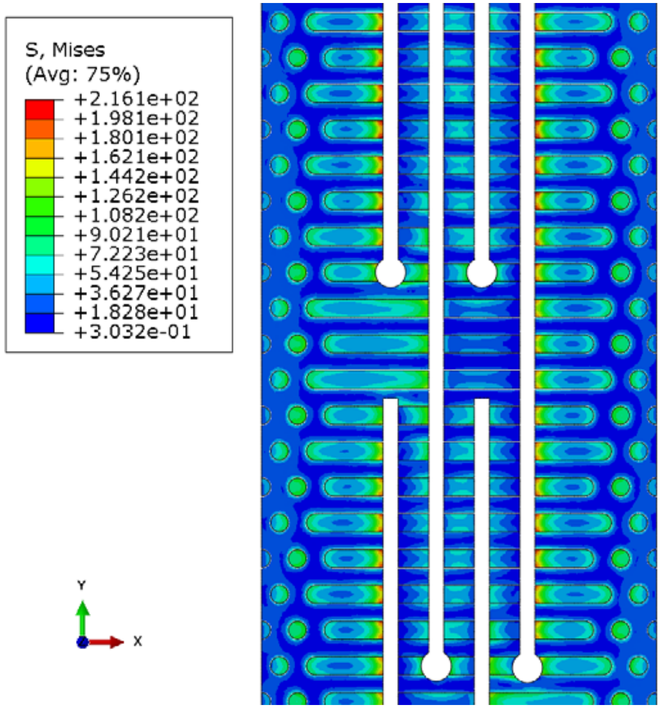
Diffusion Bonding



- Concerns with Boron as MPD for TLP due to fast diffusion
- Move to solid diffusion bonding with and w/o nickel interlayer
- Solid joint at 1150 °C
- Good joint yield/ductility at 720 °C

Design Modifications

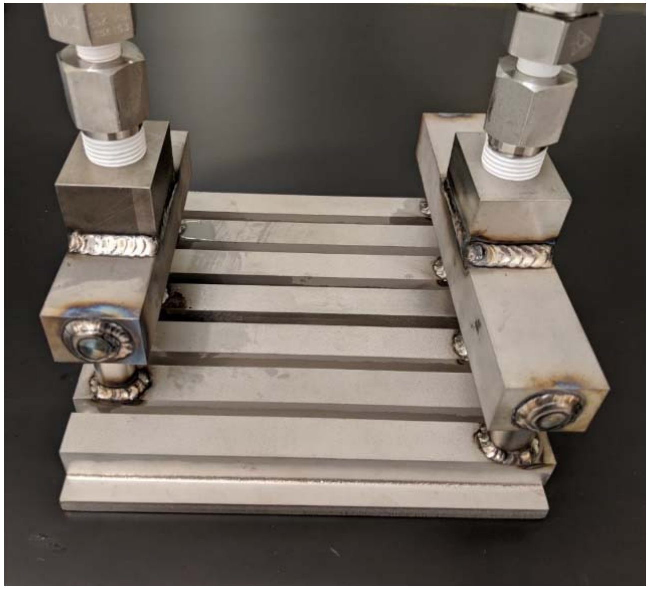


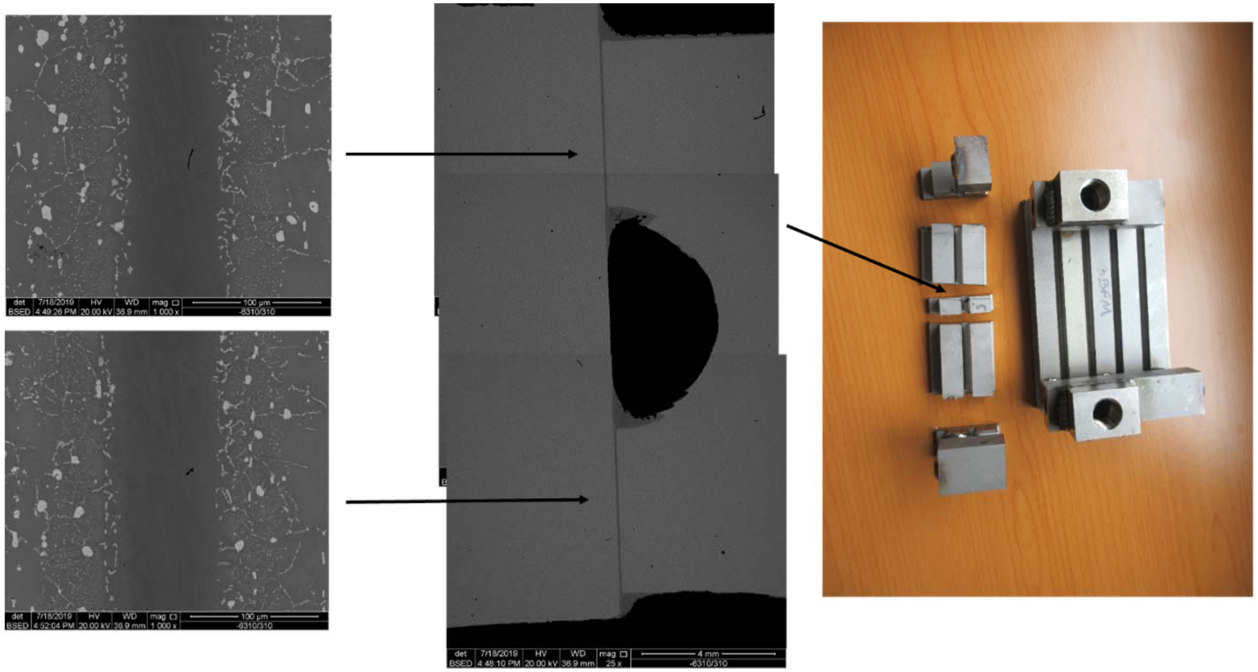


- Pin and bar more robust
- Inlet/outlet slit bonding area increased
- Qualification testing ongoing

Design Modifications

Revised Brazing Methods





- Added heat treatment (stress relief) steps
- Increased braze thickness
- Improved surface prep
- Pass proof test >83 MPa at RT
- Good joint quality

Looking Forward

- Pathway to megawatt scale demonstrated
- Modular concept advantageous
  - Tailored receiver design
  - Manufacturability
- Physical test article designed and fabricated
- On-sun testing at UC-Davis in Q4 2019

Conclusions

- High temperature/pressure sCO2 heat exchanger development is challenging and expensive
- Solar thermal application even more extreme than other devices

- Printed circuit type HX with challenges related to
  - Joining
  - Design

- Lessons
  - Lab scale bonding may not scale to component level (uneven ramp rates, non-uniform diffusion etc.)
  - Manufacturing, thermal hydraulic and mechanical must be concurrently considered in design
  - Brazing high nickel alloys is non-trivial

- I am happy to share more detailed technical information with interested parties

Acknowledgments

- R. Malhotra (Rutgers)
- S. Apte (Oregon State)
- V. Narayanan (UC-Davis)
- E. Rasouli (UC-Davis)
- Matt Carl (NETL)

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Questions?

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