High-Temperature Creep and Creep-Fatigue Performance of Stainless Steel 316 Diffusion Bonds

Paper #63

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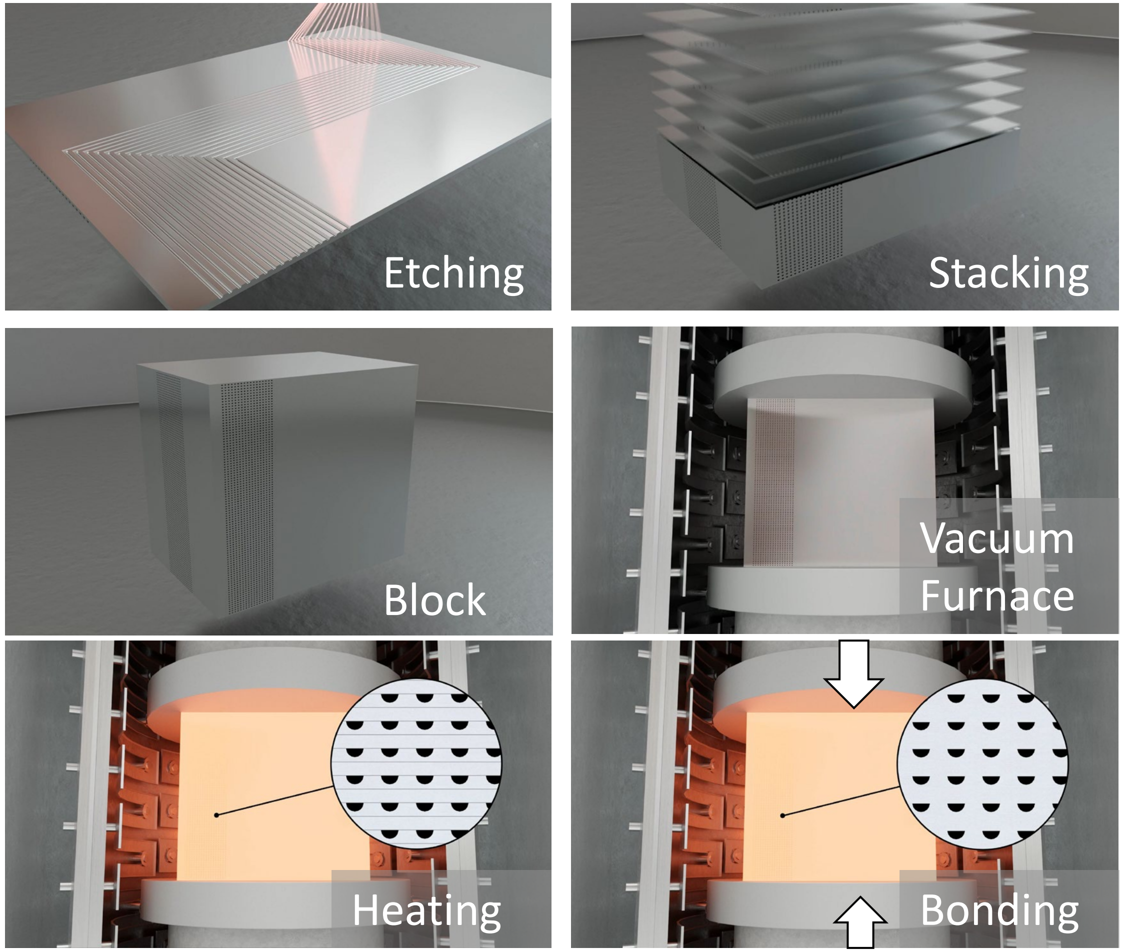
Why Diffusion Bonded Compact Heat-Exchangers (CHX)?

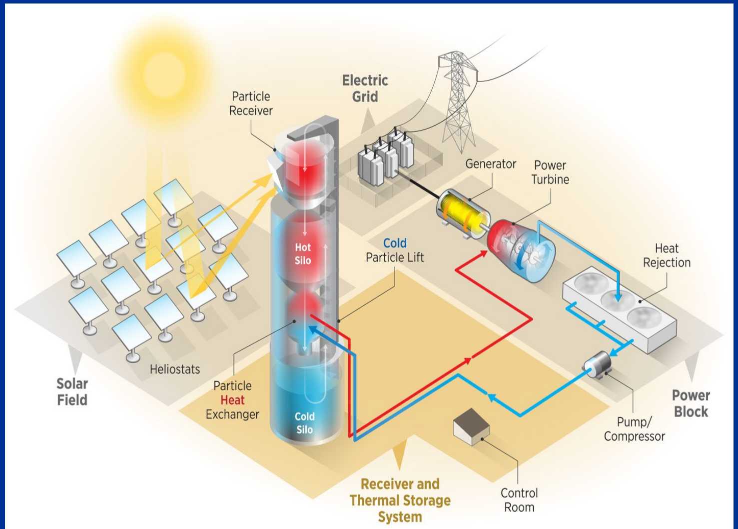
- Compact Heat Exchangers (**CHX**) are **more efficient** and have the potential to **reduce size** in many applications compared traditional heat exchangers.
- Typical Diffusion Bonding process
  - Channels are chemically etched into thin sheets / plates
  - Plates are stacked on top of each other
  - Plates are loaded under uniaxial pressure at high temperatures and bonded together to form single block

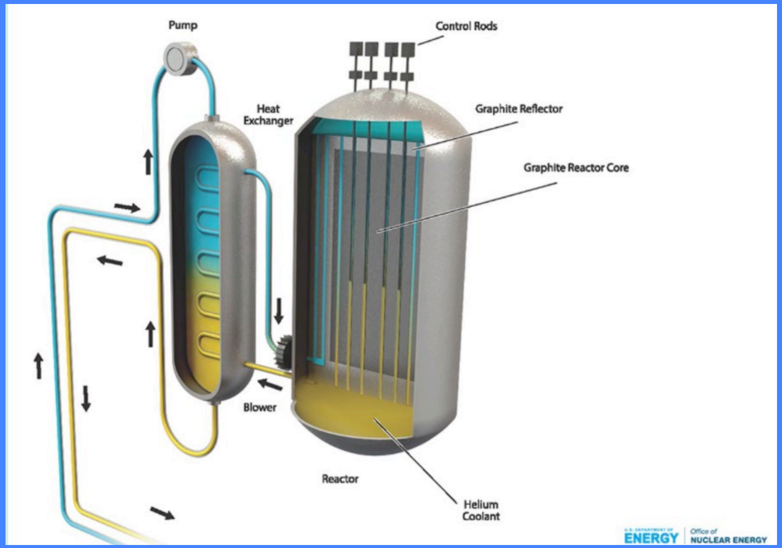


Opportunity Space for DB-CHX

- ➢ **Increasing design temp. & pressure → minimize volume of expensive alloys**
- ➢ **Weight and/or space savings**

Opportunities for Compact Heat Exchangers (CHX)





Concentrating Solar Power (CSP)

- Particle to sCO_2
- Bulk energy storage

Advanced Power Cycles

- sCO_2 Brayton Cycle
- Direct & in-direct cycles

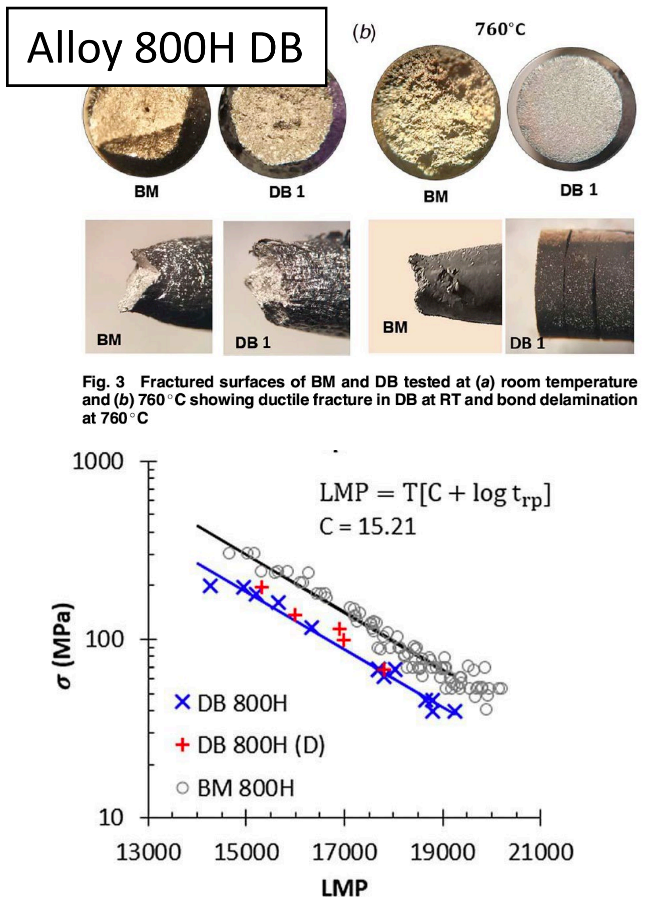
Nuclear

- Very-high-temperature (VHT) gas-cooled reactor
- Electric & non-electric applications

High-temperatures provide multiple applications for CHXs

Lifetime Modeling Diffusion Bonds (DB) at High Temperature

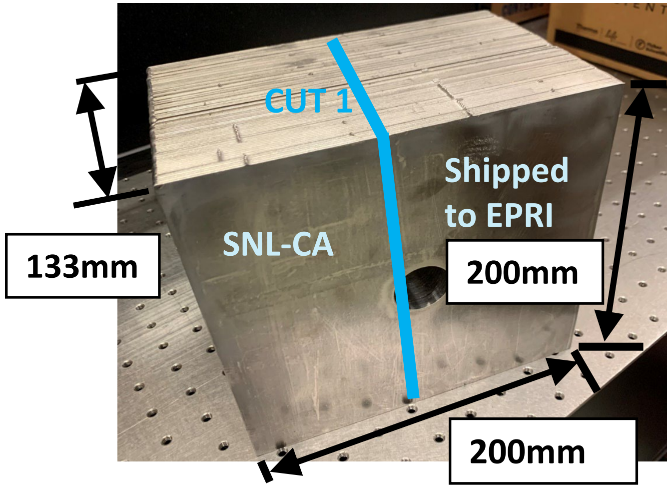
- ASME DB:
  - Manufacturing acceptance ASME Section IX QW-185, ‘diffusion welding’
  - **Section VIII design allowables: 30% penalty on stress due to weld inspection requirements**
    - *no specified lifetime for time dependent regime*
- Literature on DB performance in creep, fatigue, and ‘creep-fatigue’
  - Few studies; generally show inferior performance for higher-alloyed materials (800H, 617, …)



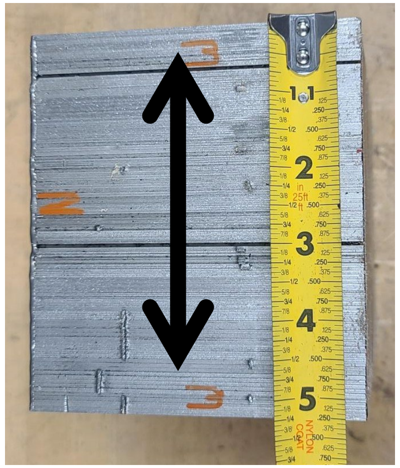
Mahajan et. al., Journal of Engineering Materials and Technology, April 2022, Vol. 144

To estimate component lifetime, what should be assumed for high-temperature material properties?

Material & Testing

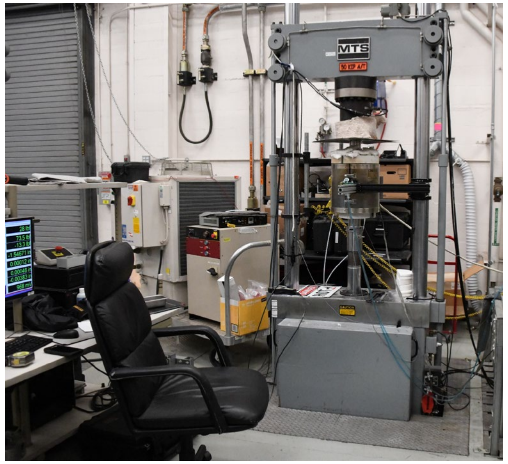


Qualification Block



Sample Test Direction

High-Temperature Testing Laboratory, EPRI



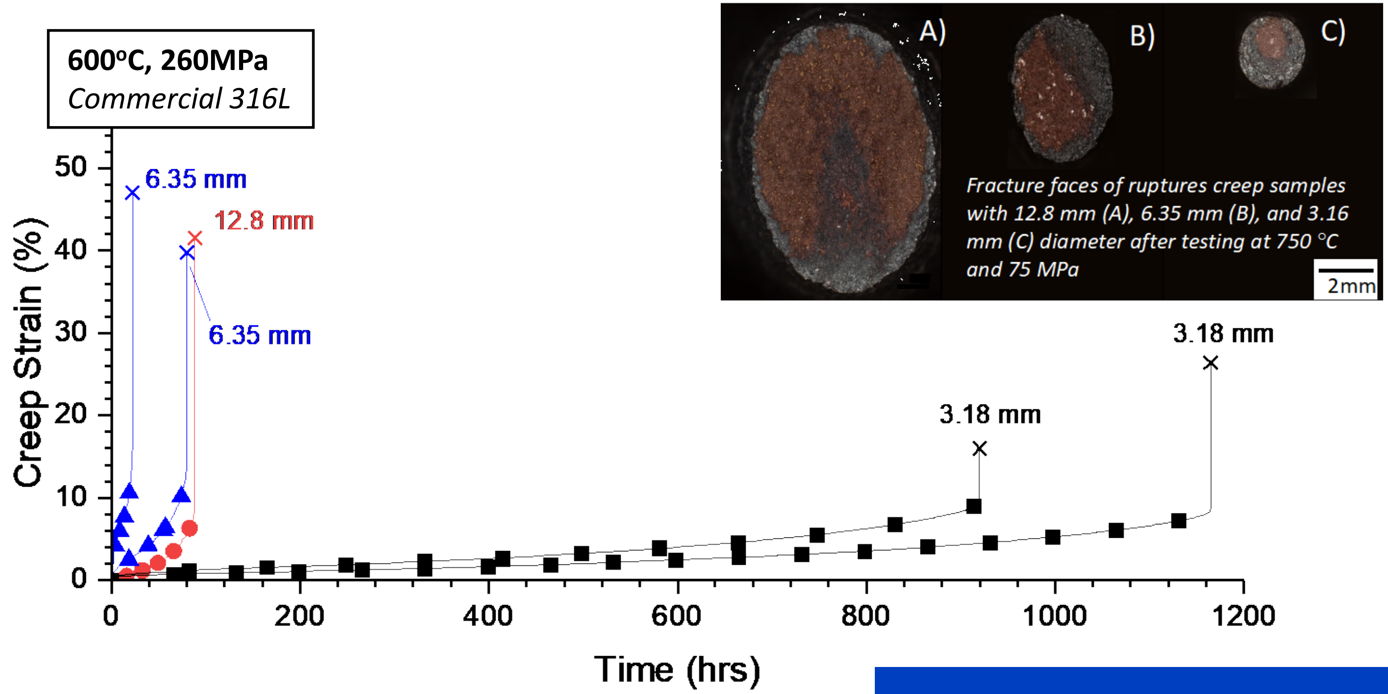
Experimental Mechanics Laboratory, SNL

	C	Si	Mn	P	S	Ni	Cr	Nb	Cu	N	B	Co	Mo	Ti
316/316L	0.08/ 0.030	0.75	2.00	0.045	0.030	10.0-14.0	16.0-18.0			0.10			2.00-3.00	
Vendor (~1.5 mm sheet)	0.021	0.48	0.91	0.036	0.001	10.1	17.1			0.040			2.03	
EPRI	0.022	0.548	0.94	0.035	<0.0005	10.07	17.233	0.037	0.411	0.0412	<0.002	0.24	2.04	<0.002

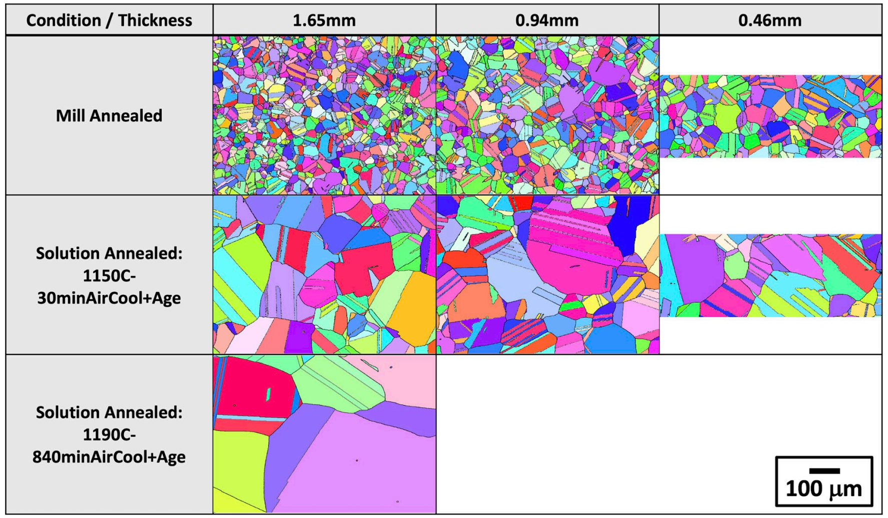
Dual listed 316/316L material: Commercial DB with today typical practice

Prior EPRI research

- Non-uniform failure (ovality) → orientation markings
- Starting sheet microstructure → testing of sheets
- Sample size effects → minimum sample gauge diameter of 6.35mm



Fracture faces of ruptures creep samples with 12.8 mm (A), 6.35 mm (B), and 3.16 mm (C) diameter after testing at 750 °C and 75 MPa

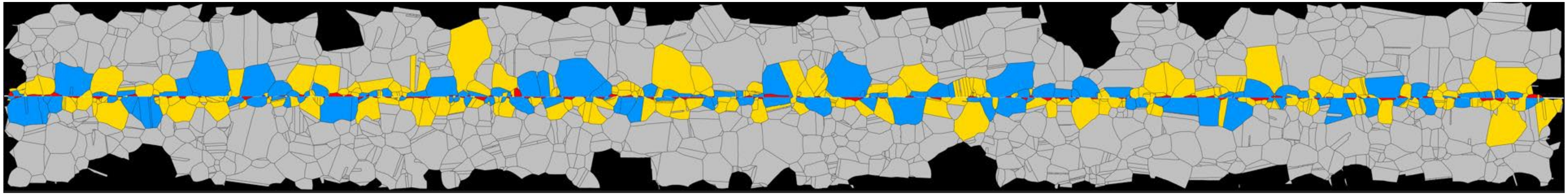


Shingledecker et. al. JMEP, 2022: [*https://doi.org/10.1007/s11665-022-07785-2*](https://doi.org/10.1007/s11665-022-07785-2)

Shingledecker, et al. ASME GT2023-102967

Test plan informed by prior EPRI research

Characterization of the 316 diffusion bond



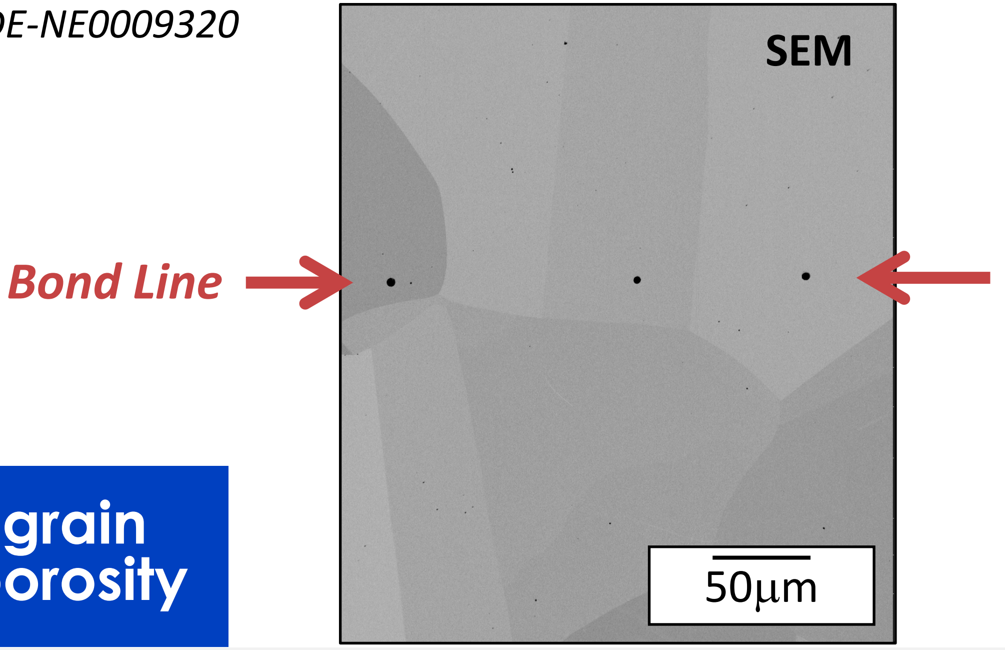
**procedure developed by DE-NE0009320*

<u>Automated OM image analysis*:</u>

Gray = all grains

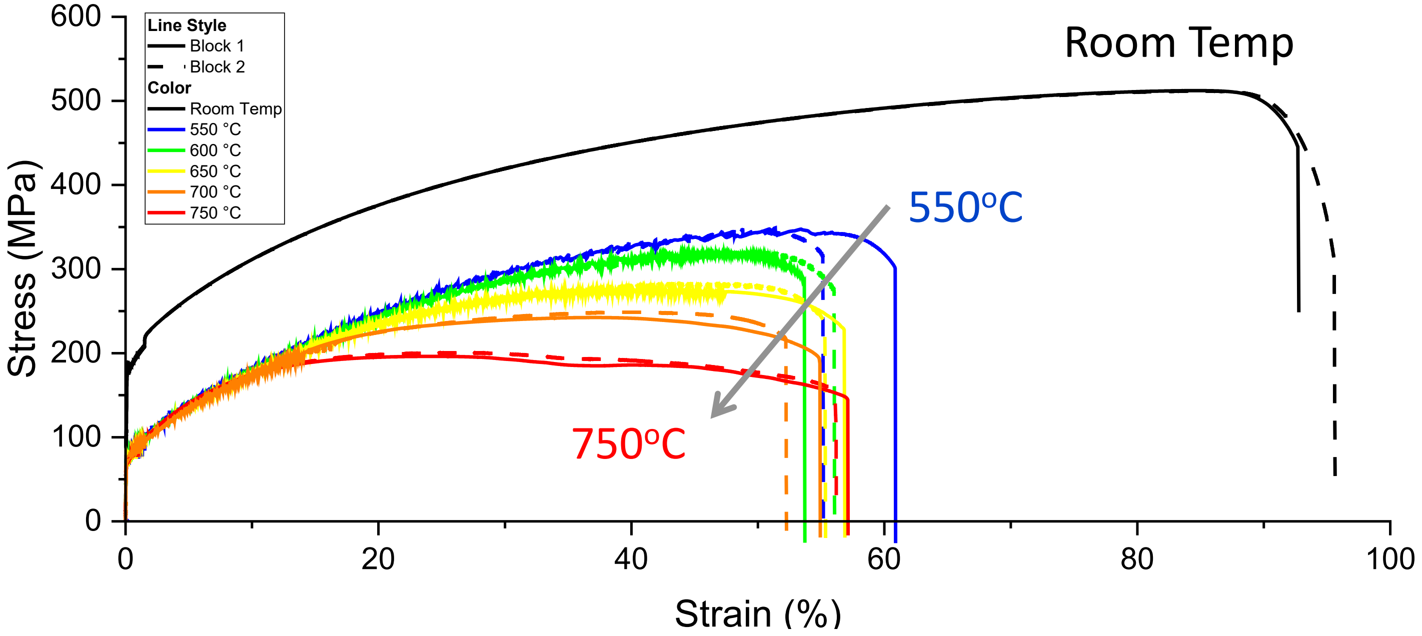
Yellow = grains near DB line (within 50μm) and with <10μm growth from DB line

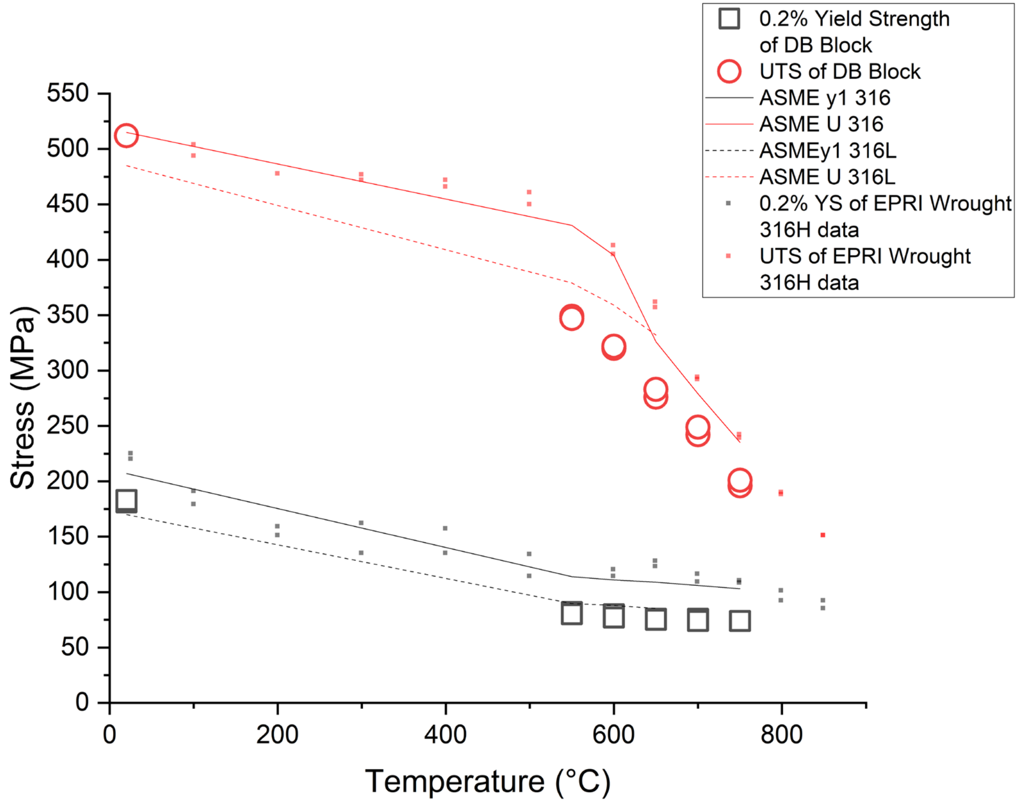
Blue/Red = grains with >10μm growth from DB line



High-quality commercial bond showing significant grain migration across bond line with minimal remaining porosity

Tensile Behavior



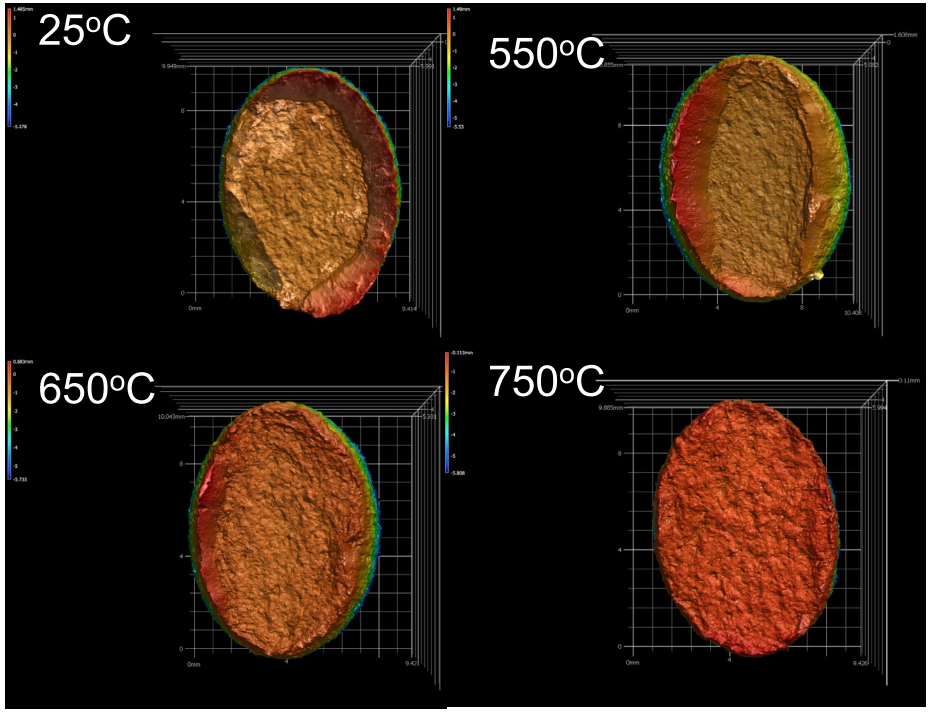


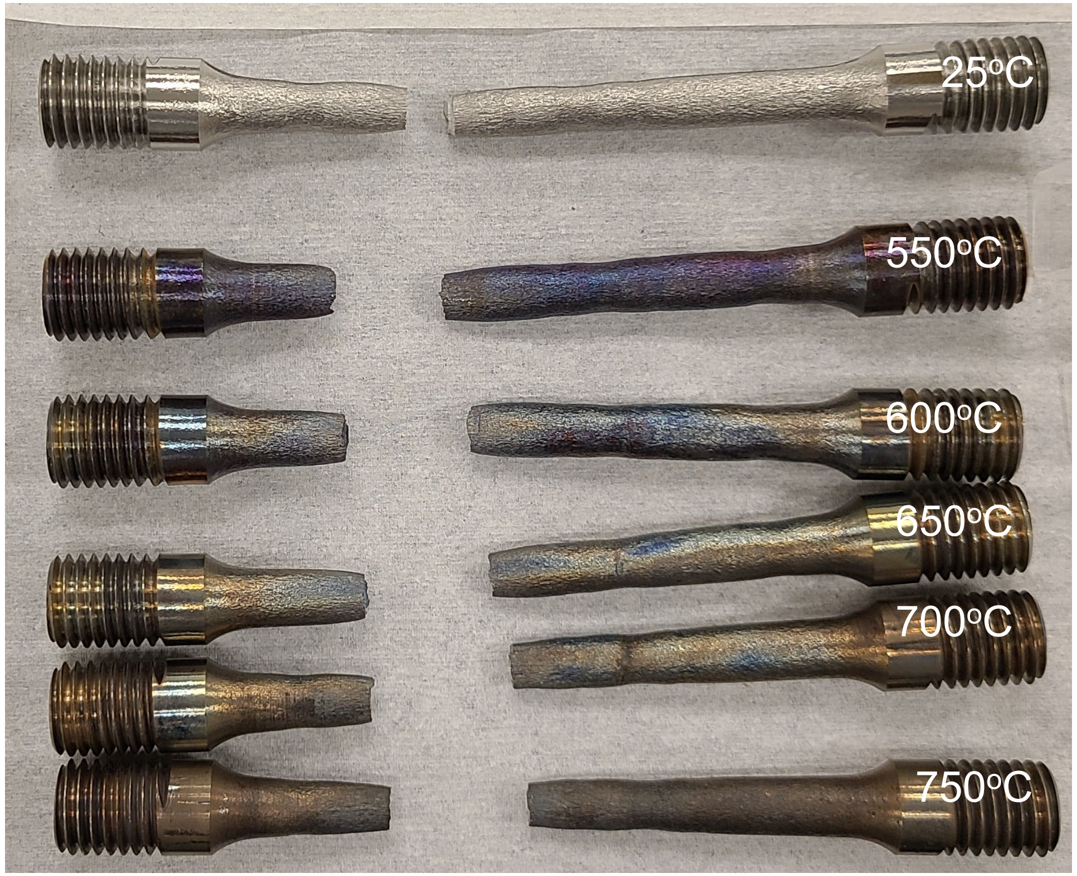
- Duplicate tests up to 750ºC
- Excellent repeatability and ductility

Similar tensile performance to wrought 316L

- Meets room temp. requirements for 316L wrought
- Elevated temperature strength slightly below ASME design curves (not statistical minimums) for wrought

Tensile – post-test

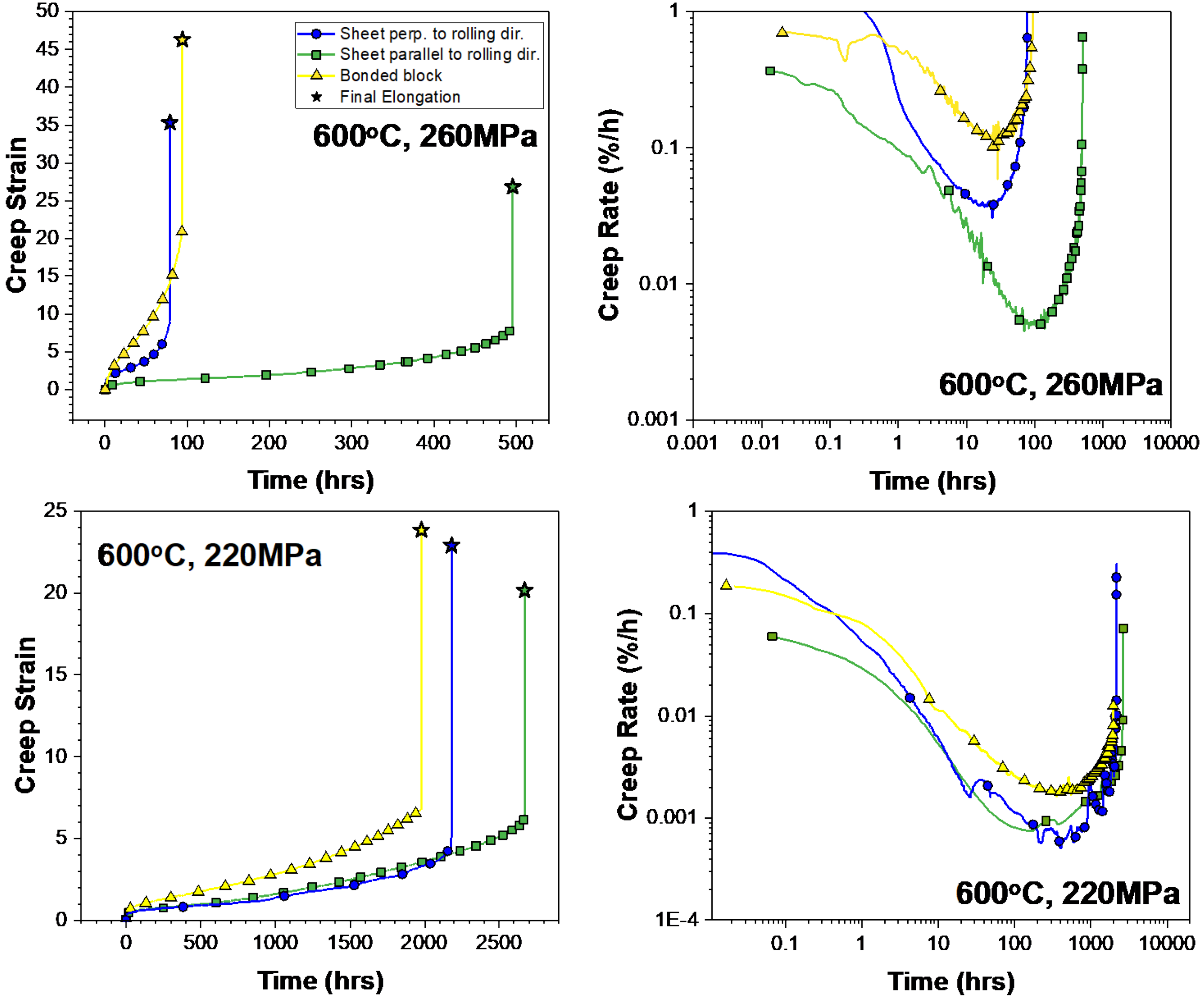




Failure appears along bond lines
Ovality in fracture faces/samples indicative anisotropy in sheet

Creep behavior

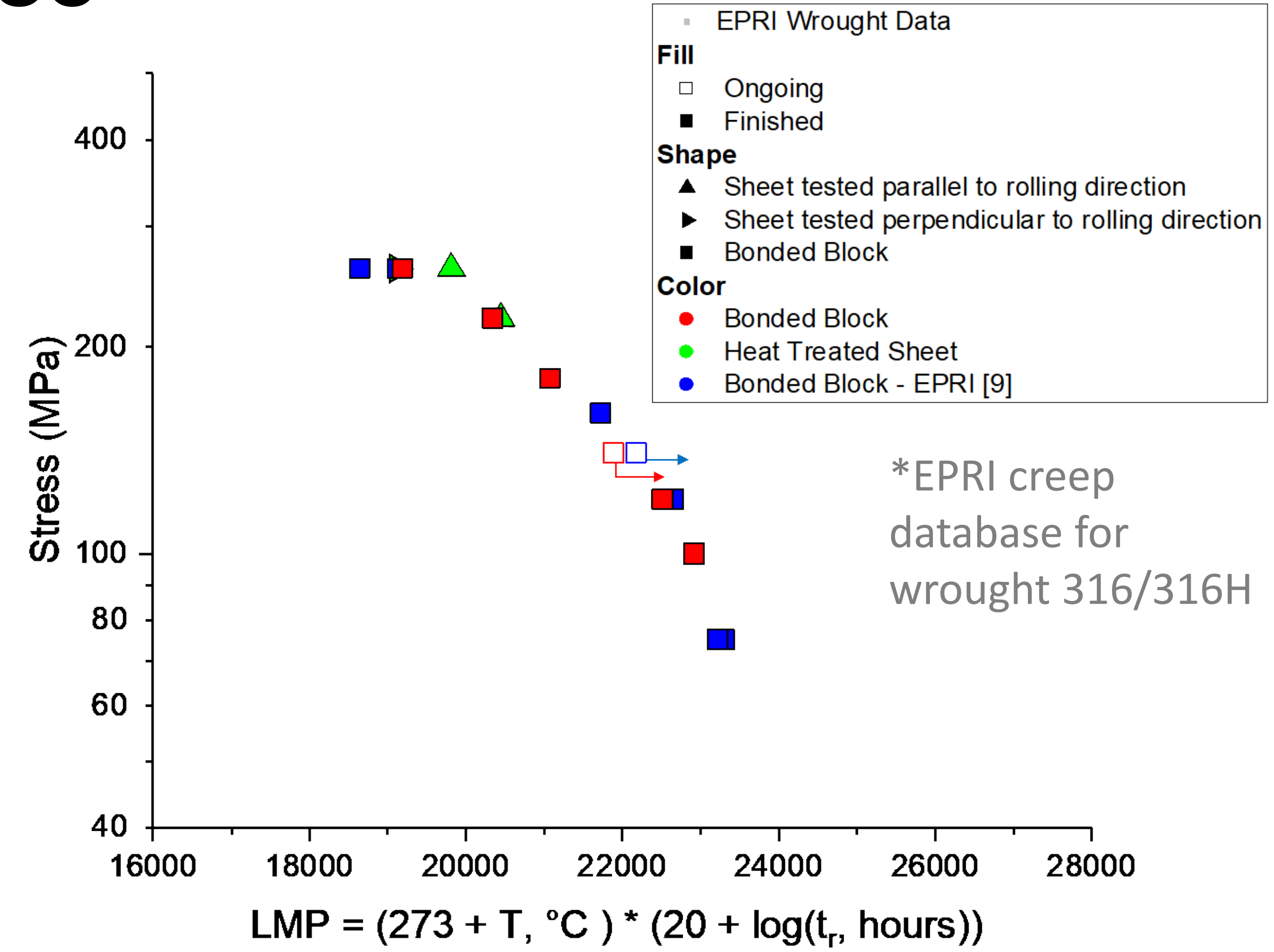
- Sheets (same heat-treatment cycle as bonding cycle):
  - At high stress, creep performance is different parallel or perpendicular to rolling direction
  - Confirmation on source of anisotropy
- Sheets compared to diffusion bonded block
  - Rupture life of weaker orientation appears to control behavior
  - Bonded blocks have similar rupture life to sheets, but higher minimum creep rate



Rupture life between DB and sheets are similar; creep deformation behavior is more complicated

Creep-rupture performance

- ~76,000 hours of creep testing to date
- Conditions:
  - 600 to 750°C
  - Longest rupture: ~7,900hrs
    - Ongoing tests (2): >11,000hrs
    - Typical rupture elongation ~40%
- Additional EPRI research (2nd DB 316/316L block)
  - No notable differences between blocks

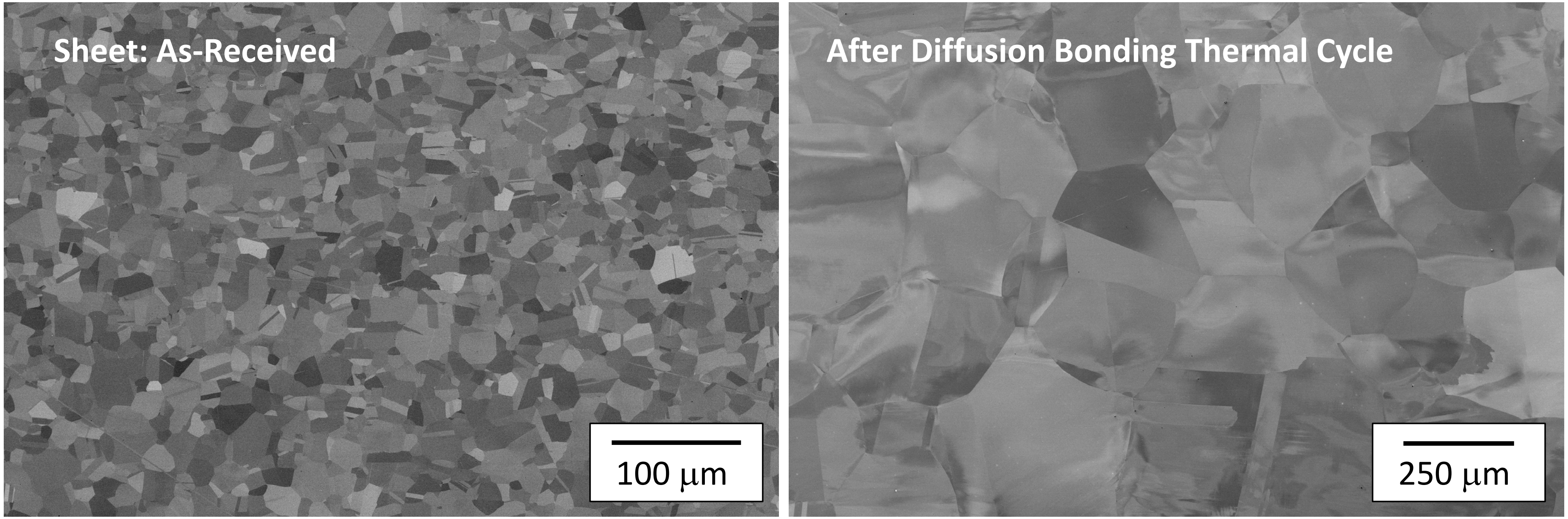


*EPRI creep database for wrought 316/316H

[9] Shingledecker, et al. ASME GT2023-102967

Intermediate to long-term creep testing show lives equivalent to wrought 316/316H

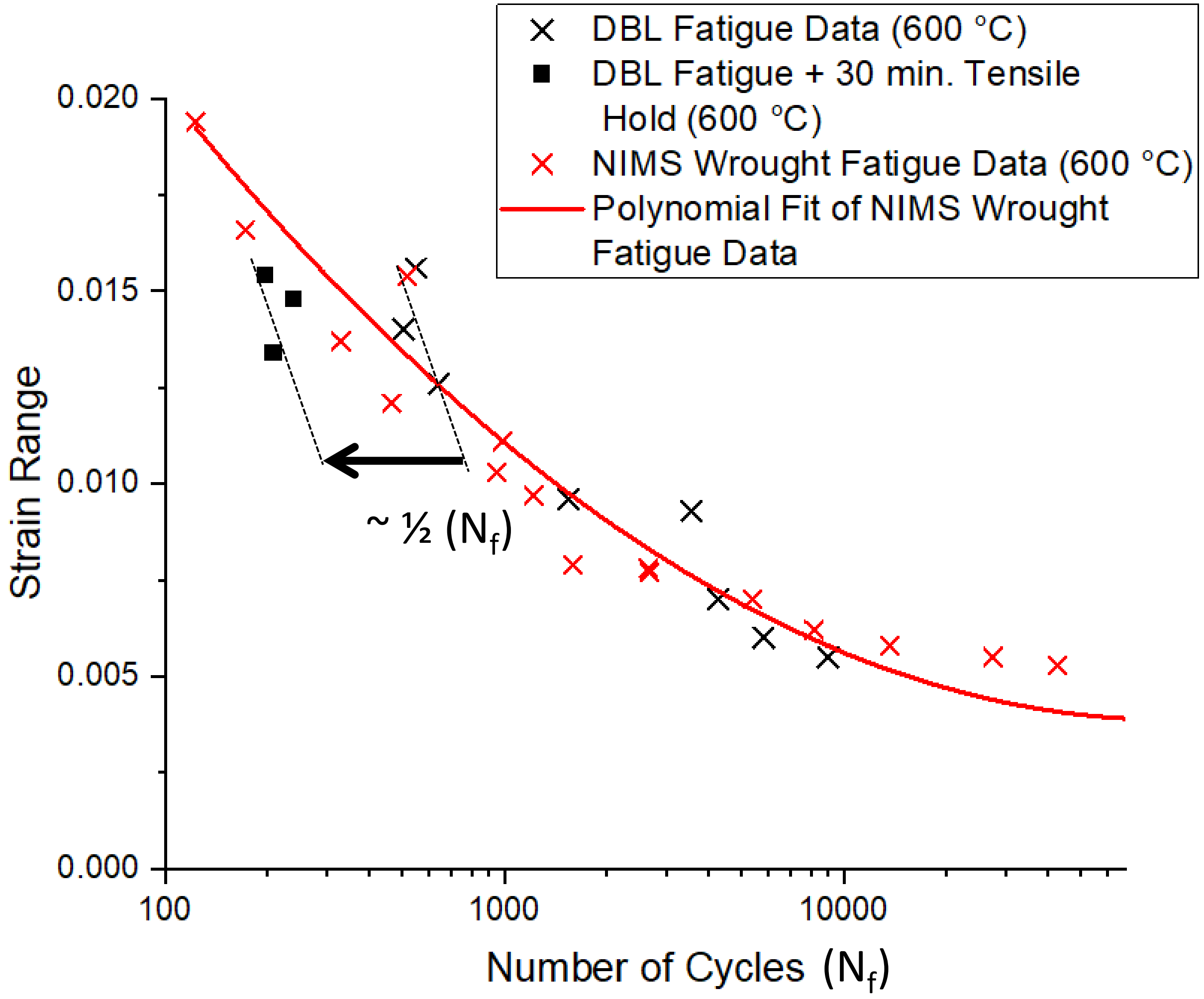
Grain Size



Coarser grain size + chemistry (C+N) likely leads to lower tensile strength but increased high-temperature creep performance for 316/316L within the 316/316H database at 600-650^{0}C

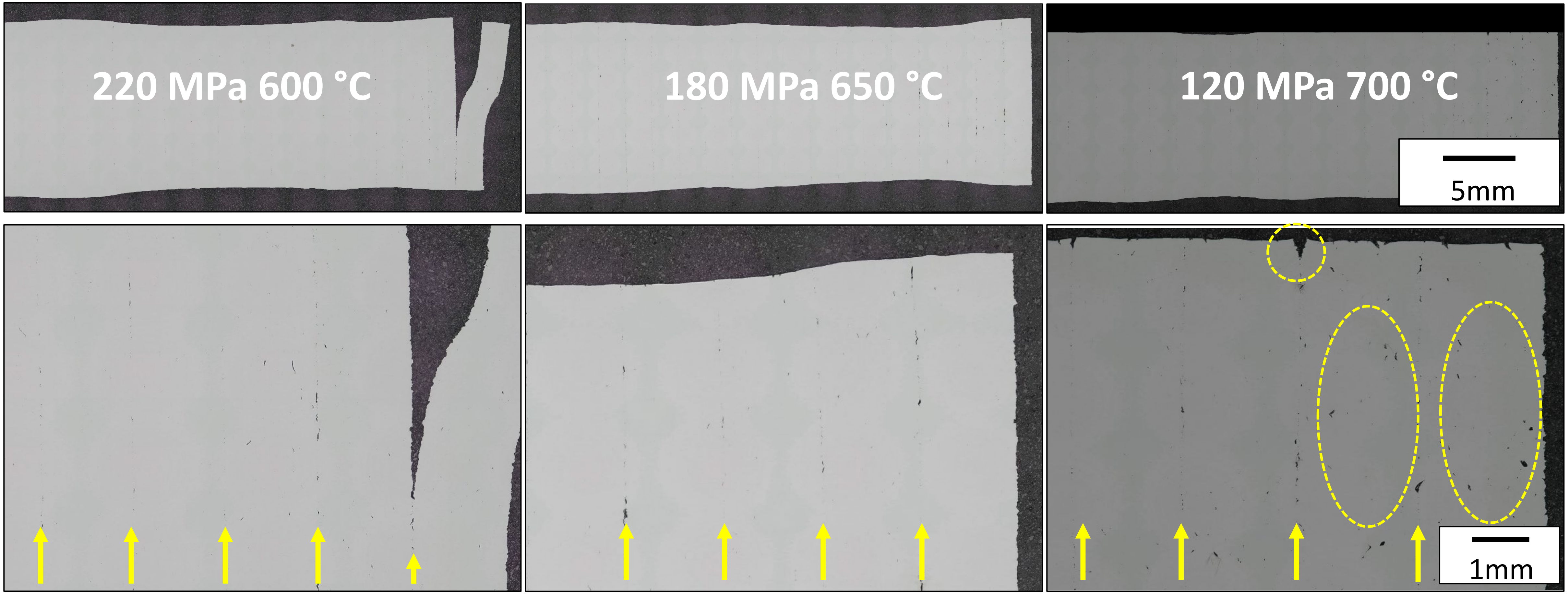
Low Cycle Fatigue (LCF)

- LCF: 600ºC
  - Similar behavior to wrought 316/316H database
  - Total strain ranges from ~0.6 to 1.6%
- LCF+Hold-Time:
  - 30 min (0.5hrs) tensile hold
  - Reduced cycle life by approximately 50%
  - Similar to observations at 550-650ºC in literature



316 DB LCF and LCF+hold-times equivalent to wrought 316/316H

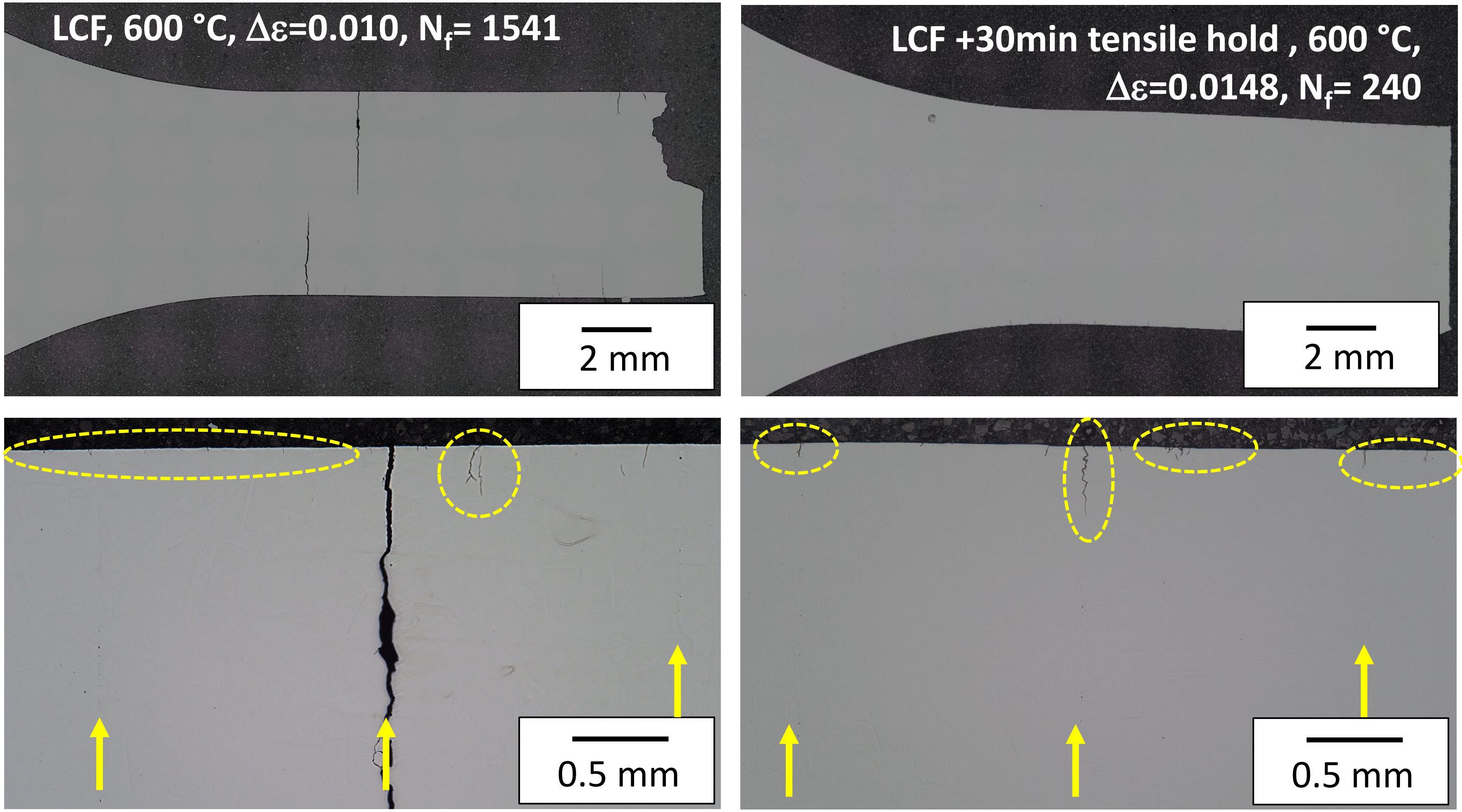
Creep damage (macroscopic)



Creep cavities form preferentially in region of diffusion bond leading to rupture, more pronounced at lower testing temperatures

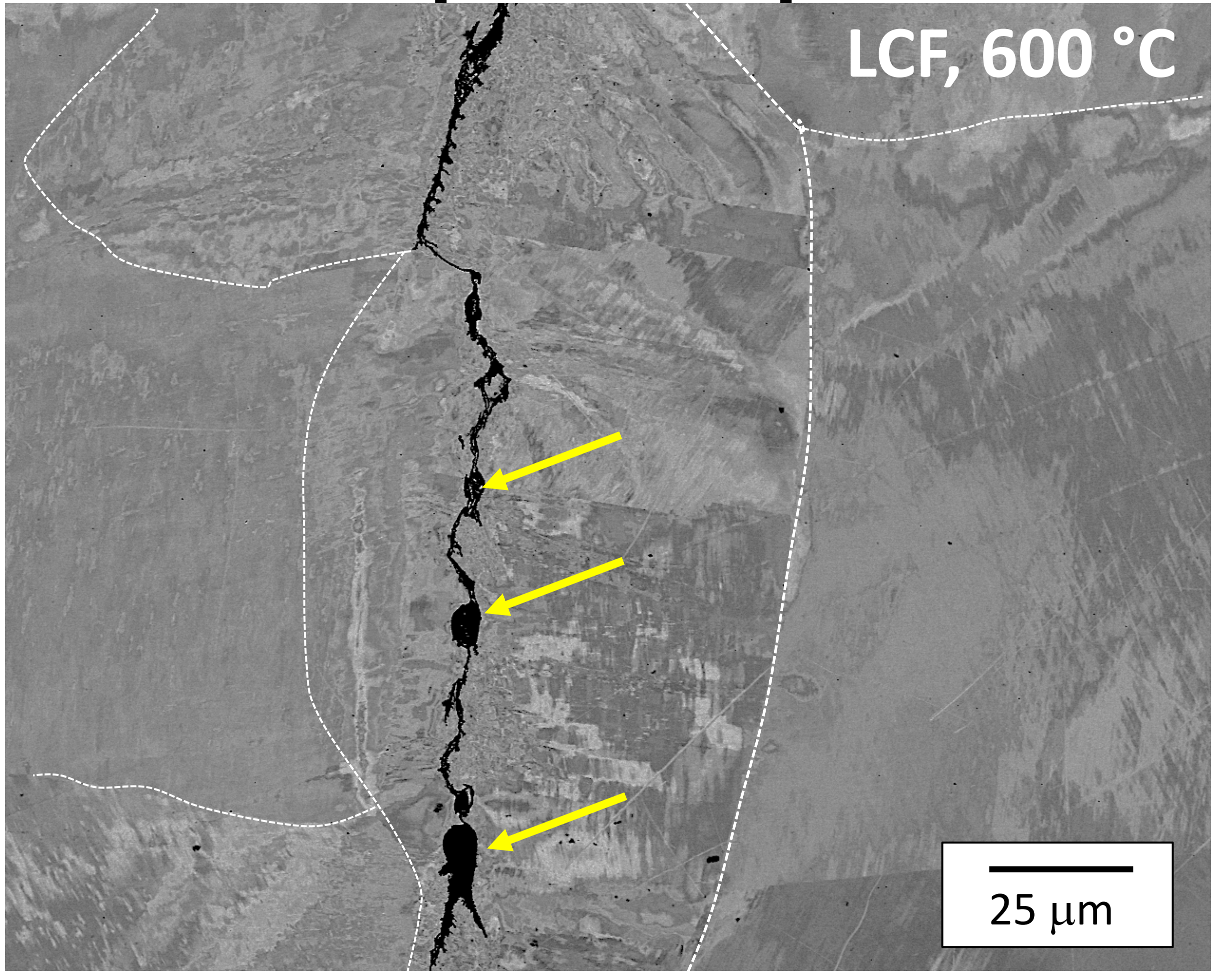
Fatigue Damage (macroscopic)

- Surface initiated damage observed
- Multiple cracks grow along original diffusion bond interface
- Fracture appears flat

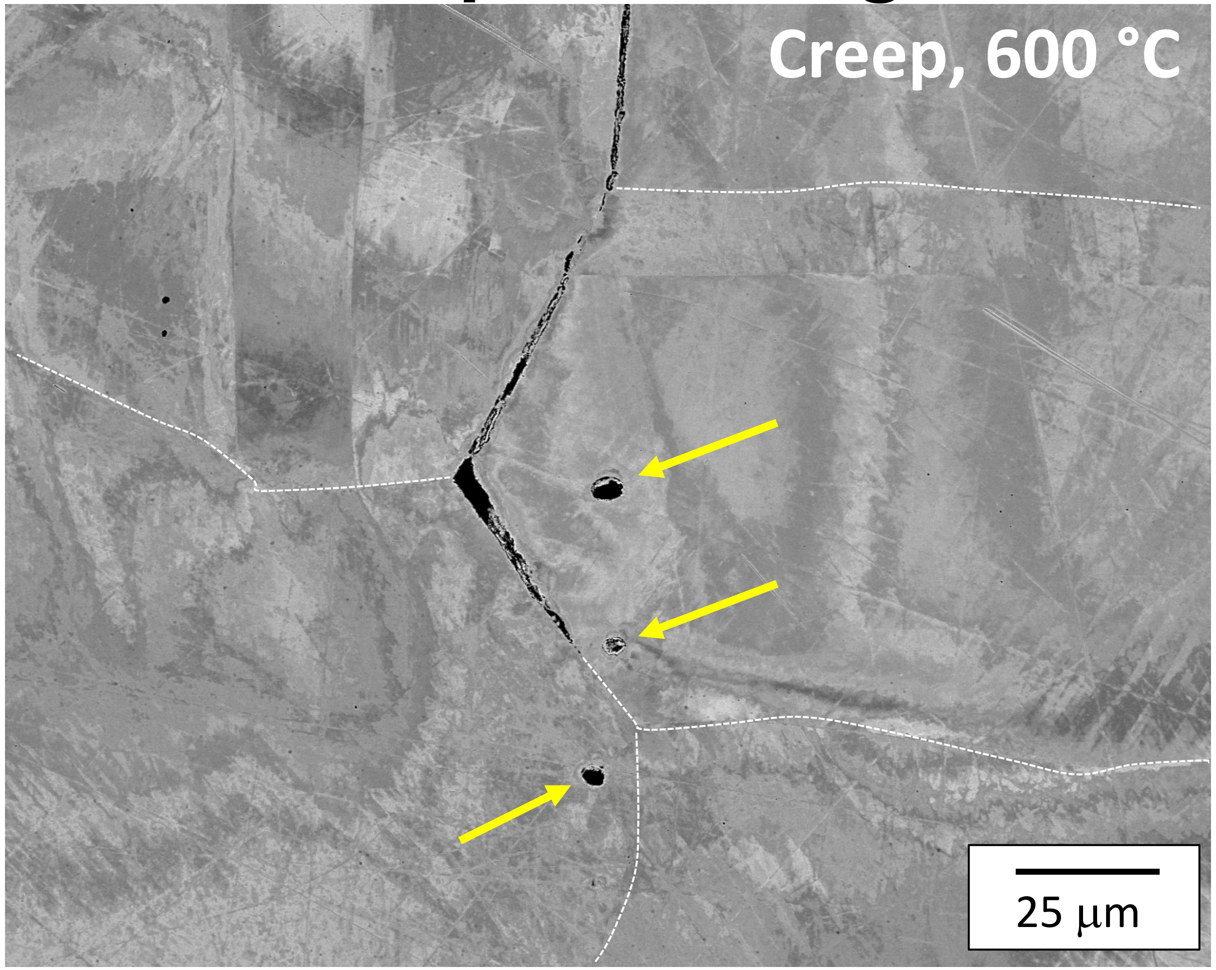


Little macroscopic difference in hold-time testing

Microscopic comparison between creep and fatigue



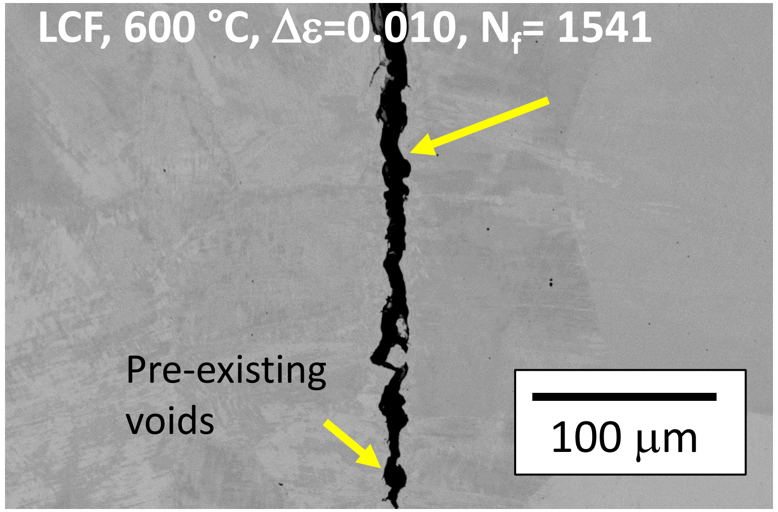
Fatigue crack grows transgranularly through pre-existing voids

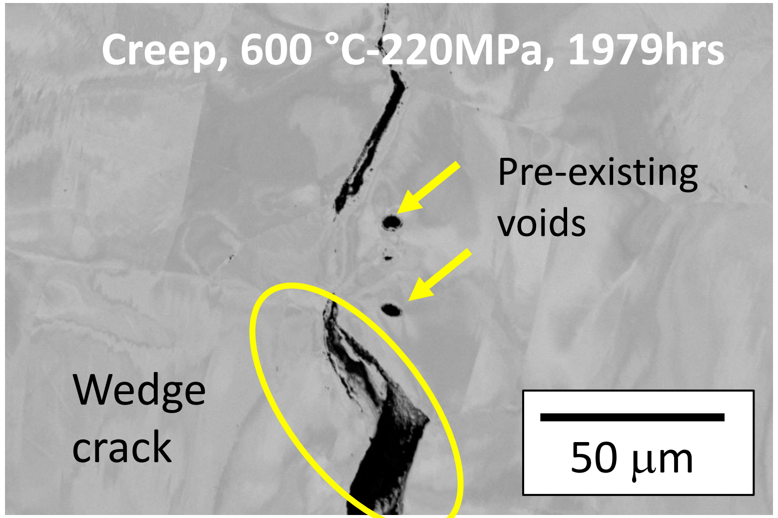


Creep damage form on grain boundaries (intergranularly) near pre-existing voids

Subtle difference in creep and fatigue, what about hold-time fatigue?

High-Temperature Damage

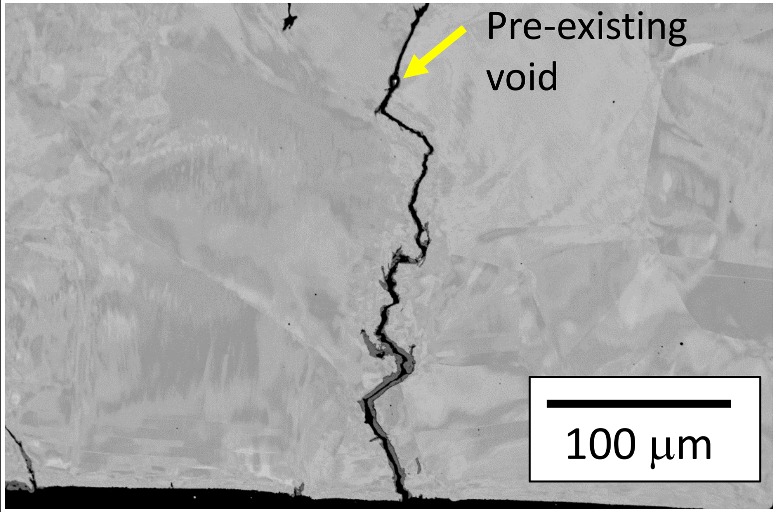


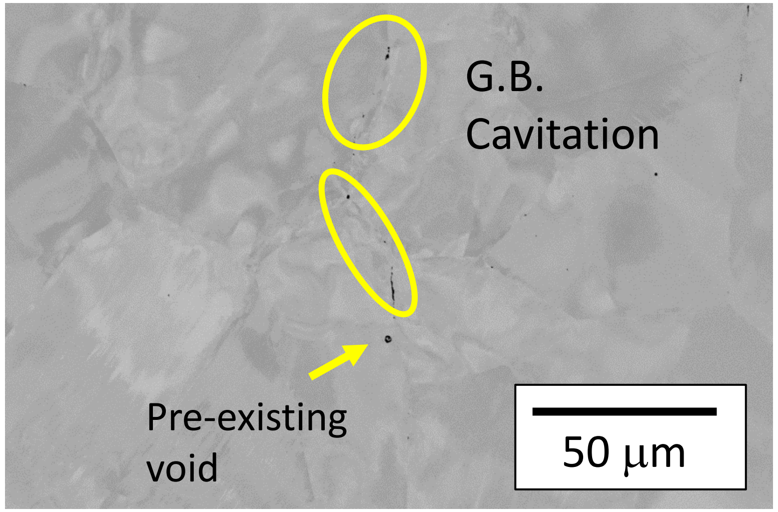


Testing	Initiation	Growth
LCF	Surface (multiple location)	Transgranular with preference for diffusion bond line and pre-existing voids
Creep	Grain boundaries	Intergranular (near original diffusion bond interface): wedge cracks, G.B. decohesion
LCF + Hold Time	Surface (multiple locations, trans- or intergranular)	Intergranular (near original diffusion bond interface): cavities, G.B. decohesion, wedge cracks

Macro + microscopic evaluation suggest LCF+Hold-Time results in time dependent ('creep-fatigue') damage

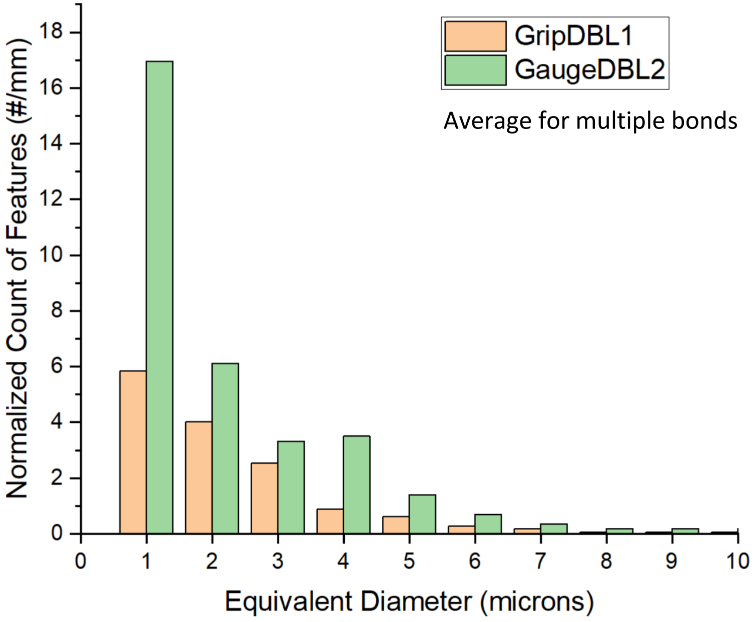
LCF +30min tensile hold , 600 °C, $\Delta\varepsilon$=0.0148, N_f= 240



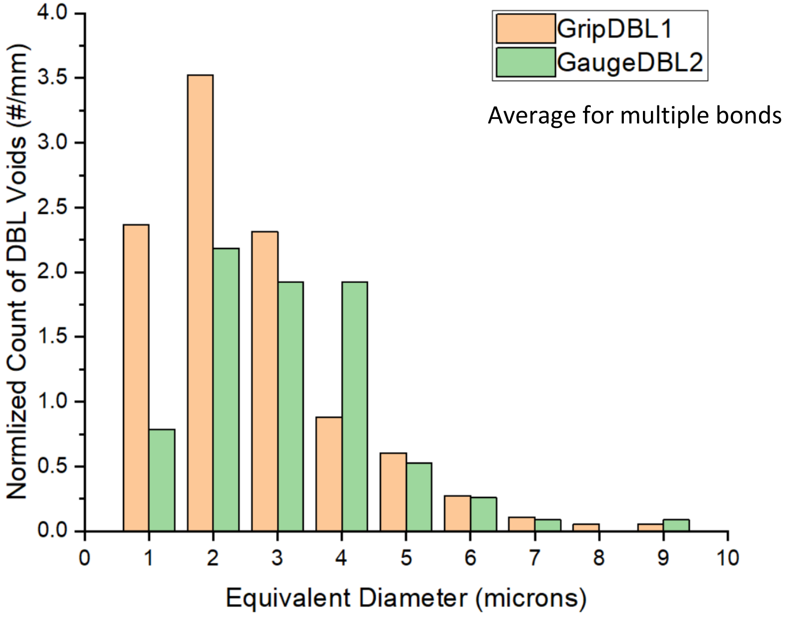


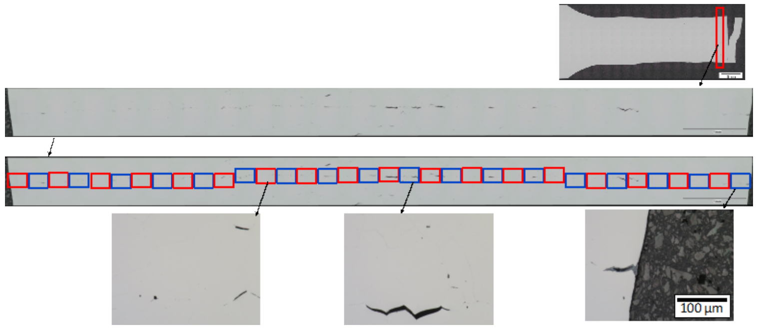
Role of pre-existing voids and creep

Total Features Measured:
Voids + Creep at DB Line

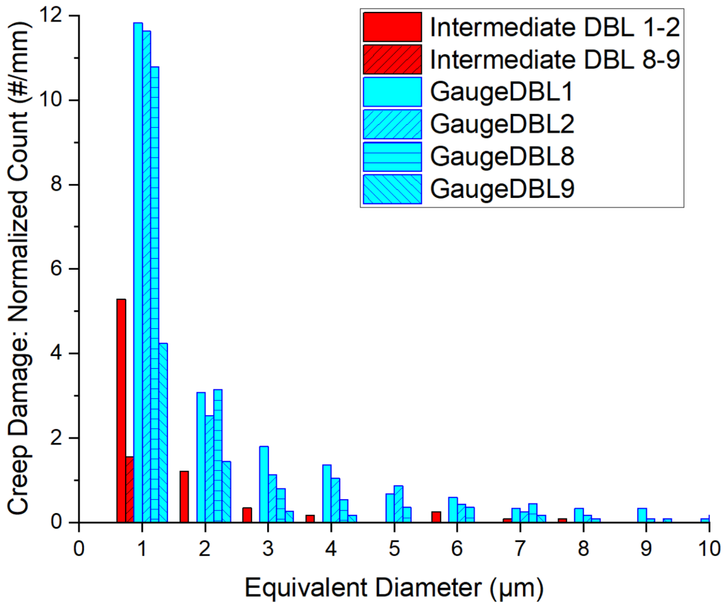


DB Line Voids Only for Grip (no creep) to Gauge (creep)



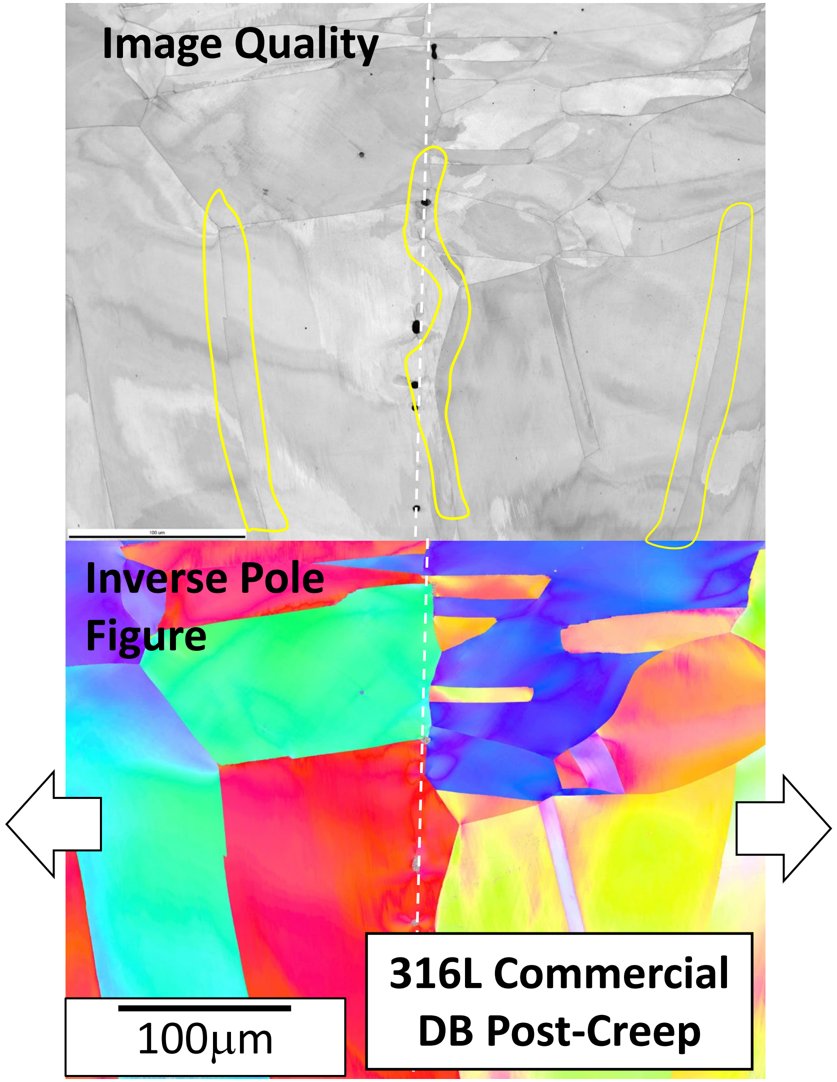


Creep Damage in Gauge at DB Line compared to intermediate regions between bonds

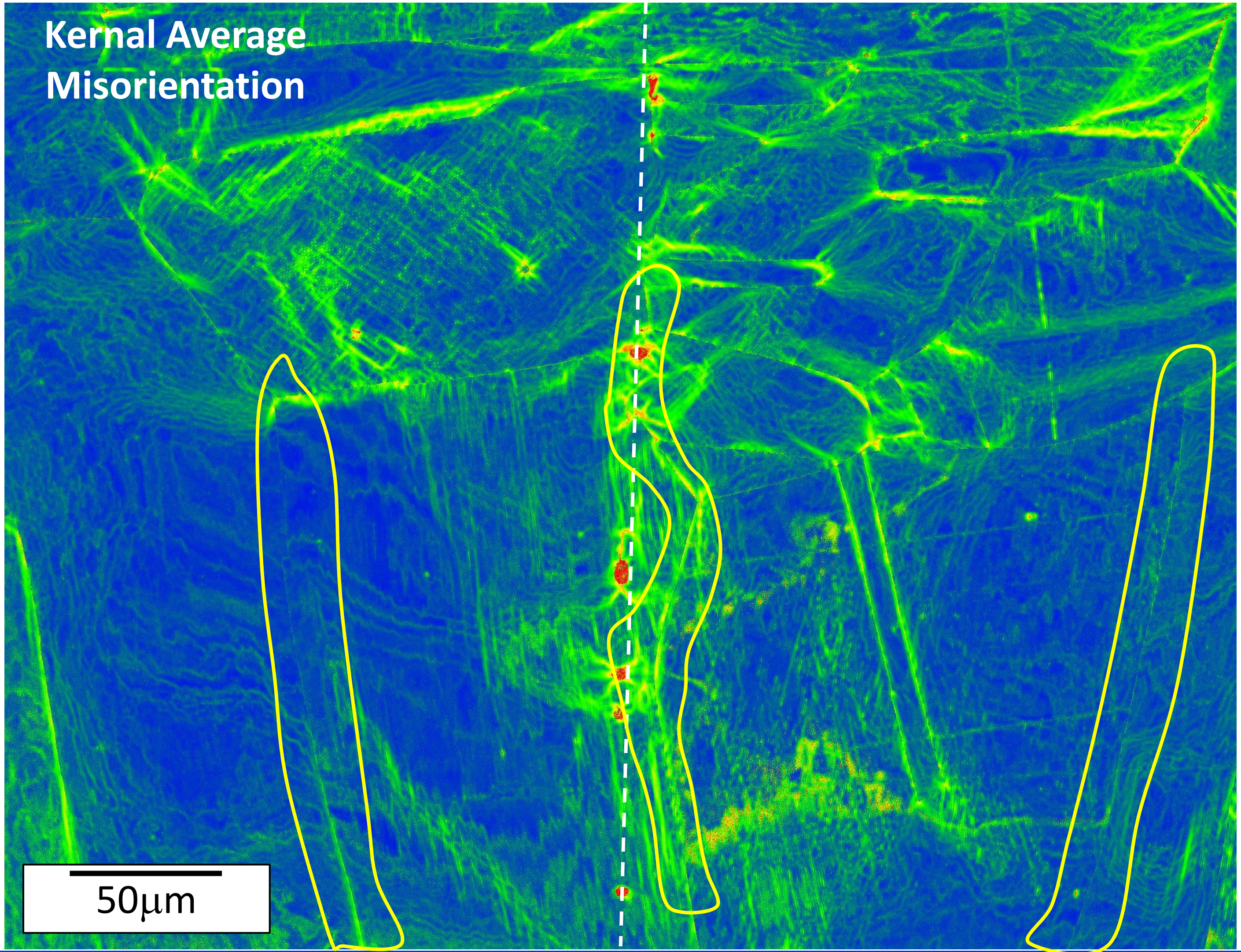


Detailed quantitative analysis confirms pre-existing DB voids not coincident with grain boundaries do not initiate new creep damage or grow appreciably during creep

Creep damage: why does failure occur near original DB interface?



7th Diffusion bond line from failure location after creep testing (arrows indicate applied stress)



Pre-existing porosity may lead to stress concentrations, strain (creep damage) appears higher on grain boundaries near diffusion bond even with grain migration across bond line

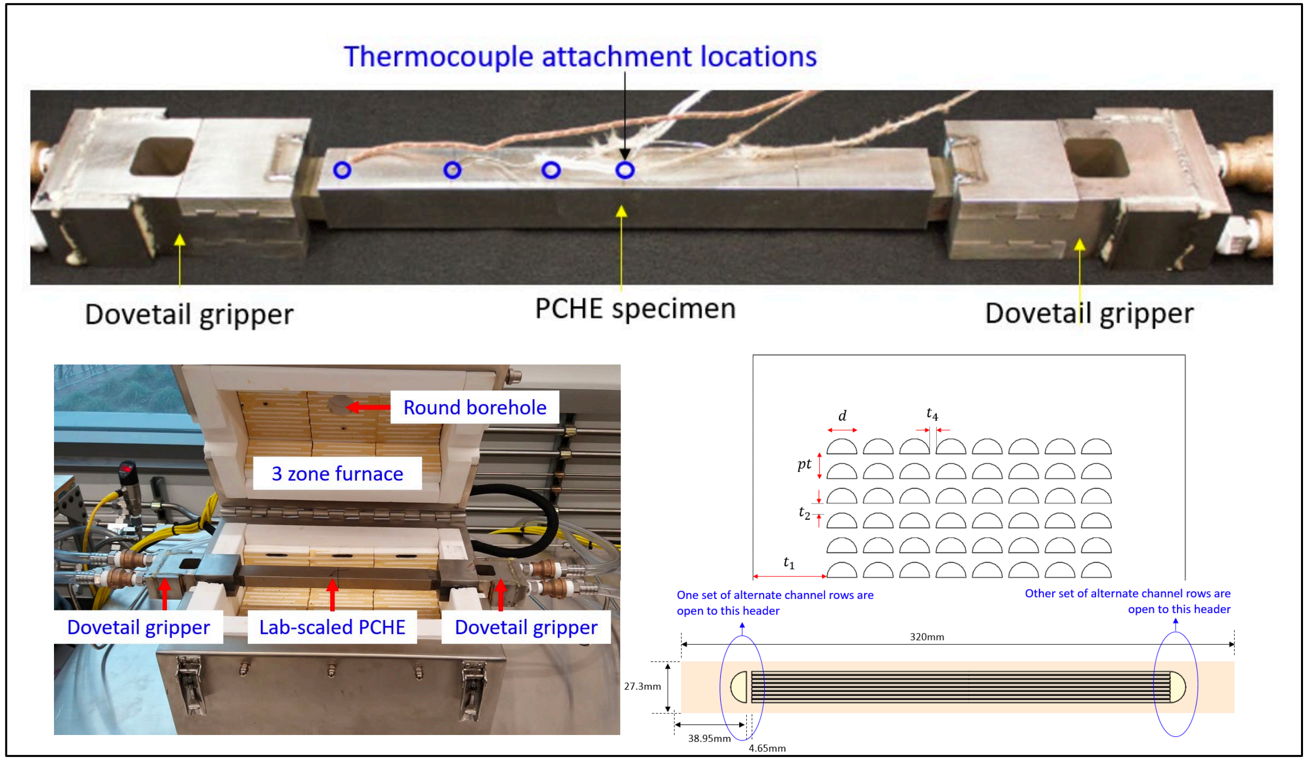
Summary

- Significant first-of-a-kind test program was conducted on 316/316L diffusion bonded blocks to understand high-temperature material performance:
  - High-temperature tensile behavior was at the bottom of the scatterband but good ductility and repeatability was observed
  - Creep-rupture life was within the 316/316H scatterband with good creep ductility for times beyond 10,000 hrs likely due to material chemistry and grain size effects
    - Non-isotropic creep behavior (rupture ovality) is directly linked to creep performance in the sheets even after thermal treatment
  - A LCF cycles to failure (S-N) was established and is inline with expectations for 316/316H.
  - Initial creep-fatigue results show a 30 min hold-time reduce cycle life by approximately ½ which is consistent with published literature on wrought 316.
- Despite high strength and good ductility failure at high-temperature appeared macroscopically planar at diffusion bonding interfaces
  - Detailed metallurgical investigation shows that damage mechanism was influenced either directly or indirectly due to pre-existing voids from manufacturing depending on loading conditions

Data suggest for lifetime estimation and design using existing wrought databases for 316 is appropriate and a strength reduction factor is not needed

Next steps

- This test program:
  - Uniaxial loading
  - Bonded sheets
- Applications:
  - Multiaxial loading
  - Complex microchannel designs



MAHAJAN, HERAMB PRAKASH. NC State Thesis: Mechanical Characterization and Simulation Modeling of Printed Circuit Heat Exchangers for High Temperature Nuclear Application.

Feature testing is needed to understand fundamental diffusion bond creep performance to diffusion bonded component performance

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