High-Cycle Fatigue Behavior of SiC-based Ceramic Matrix Composites (CMCs) at High Temperatures

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11th International Conference on High Temperature Ceramic Matrix Composites (HTCMC'11)
Symposium 10: Testing and Evaluation of Composites (Thermomechanical Behavior and Performance of Composites / Standard and DB)
Jeju, Korea
August 27th-31st, 2023

Funded by NASA Hybrid Thermally Efficient Core (HyTEC) Project

Outline

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- ❑ Material, Specimens, and Test Conditions
- ❑ High Temperature, High-Cycle Fatigue (HCF) without & with Simulated Cooling Holes
- ❑ Room Temperature Baseline Tensile Strength Tests on Specimens without & with Holes and Residual Tensile Strength of Runout Specimens in HCF
- ❑ Acoustic Emission (AE), Digital Image Correlation (DIC), Fractography, and Crack Formation Results
- ❑ Stress-Dependent Crack Density Evolution Derived from AE
- ❑ Correlation between AE Location and DIC
- ❑ Summary
- ❑ Acknowledgements

Background and Objective

- ❑ Ceramic matrix composites (CMCs) allow higher inlet temperatures for turbine engines which increases the thermodynamic efficiency and lower specific fuel consumption
- ❑ Uncooled CMCs utilized for power turbine blades[1] to improve performance of advanced turboshaft engine (Army & GE-Aviation)
- ❑ If CMC turbine blades can be cooled actively, turbine inlet temperatures can be increased further to gain additional engine efficiency

- ✓ Therefore, NASA and GE Aerospace collaborated in a 2-year contract to design a cooled CMC blade for a high-pressure turbine (HPT)
- ✓ In support of this study, we examined the high temperature, high-cycle fatigue behavior of a CMC without and with simulated cooling holes and evaluated retained tensile strength of the CMC to investigate failure modes

Final Report Available on NTRS Website:
ntrs.nasa.gov
Search: CMC Turbine Blade Durability

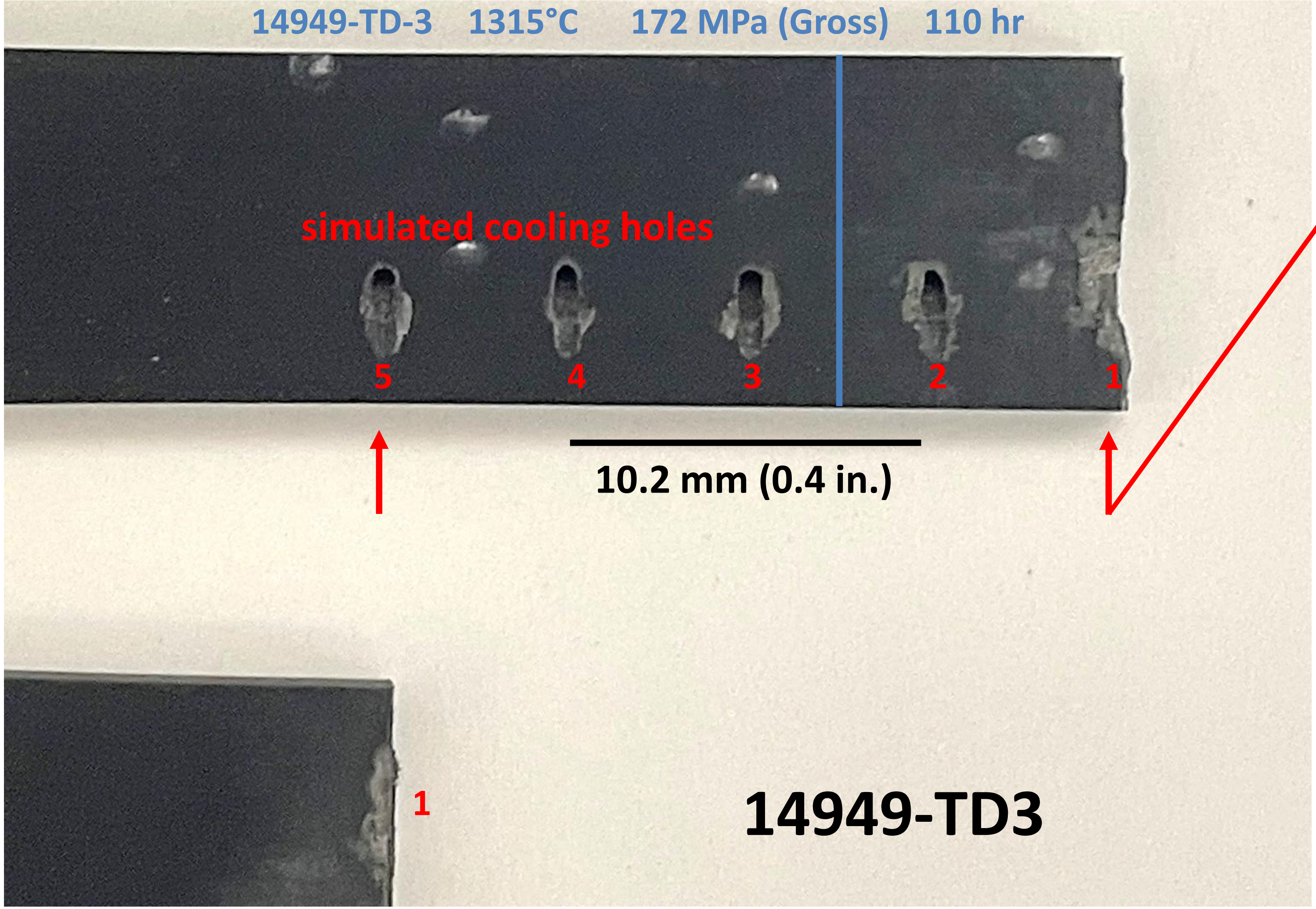
[1] D. A. Lewis, M. T. Hogan, J. McMahon, and S. Kinney "Application of Uncooled Ceramic Matrix Composite Power Turbine Blades for Performance Improvement of Advanced Turboshaft Engines," Presented at the American Helicopter Society's 64th Annual Forum, Montreal, Canada, April 29- May 1, 2008

Material, Specimens, and Test Conditions

- SiC/SiC CMC fabricated by GE Aviation[2] using a pre-preg/melt infiltration process
- Hi-Nicalon™ Type S SiC fiber; $[0°/90°/0°]_3$ ply architecture
- Tensile specimens without holes: 25.4 mm (1 in.) uniform gage length [Overall length: 152 mm (6 in.), gage section width: 10.2 mm (0.4 in.), and as-received thickness: approx. 2 mm (0.079 in.)]
- Tensile specimens with holes: Five evenly spaced horizontal holes oriented 20° to the surface (fabricated with electrical discharge machining); hole diameter: 0.66 mm (0.026 in.) [Net cross-section reduced by 23%]
- High-cycle fatigue tests at 816 and 1315°C (1500 and 2400°F)
- Testing frequency: 30 Hz; R-ratio: 0.6; Runout: 30 million cycles (278 hours)
- Baseline and HCF runout retained tensile strength tests on specimens at room temperature with DIC and AE

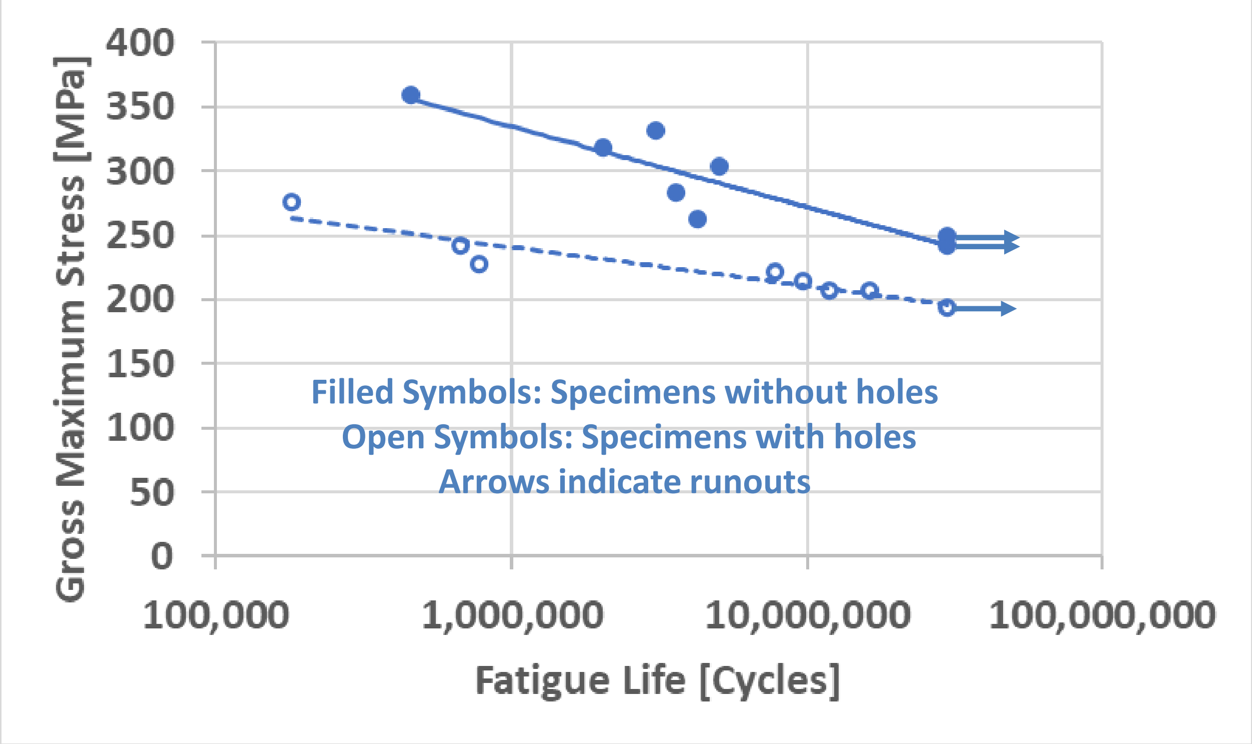
[2] J. Steibel, "Ceramic Matrix Composites Taking Flight at GE Aviation," American Ceramic Society Bulletin, Vol. 98, No. 3, April 2019, pp. 30-33.

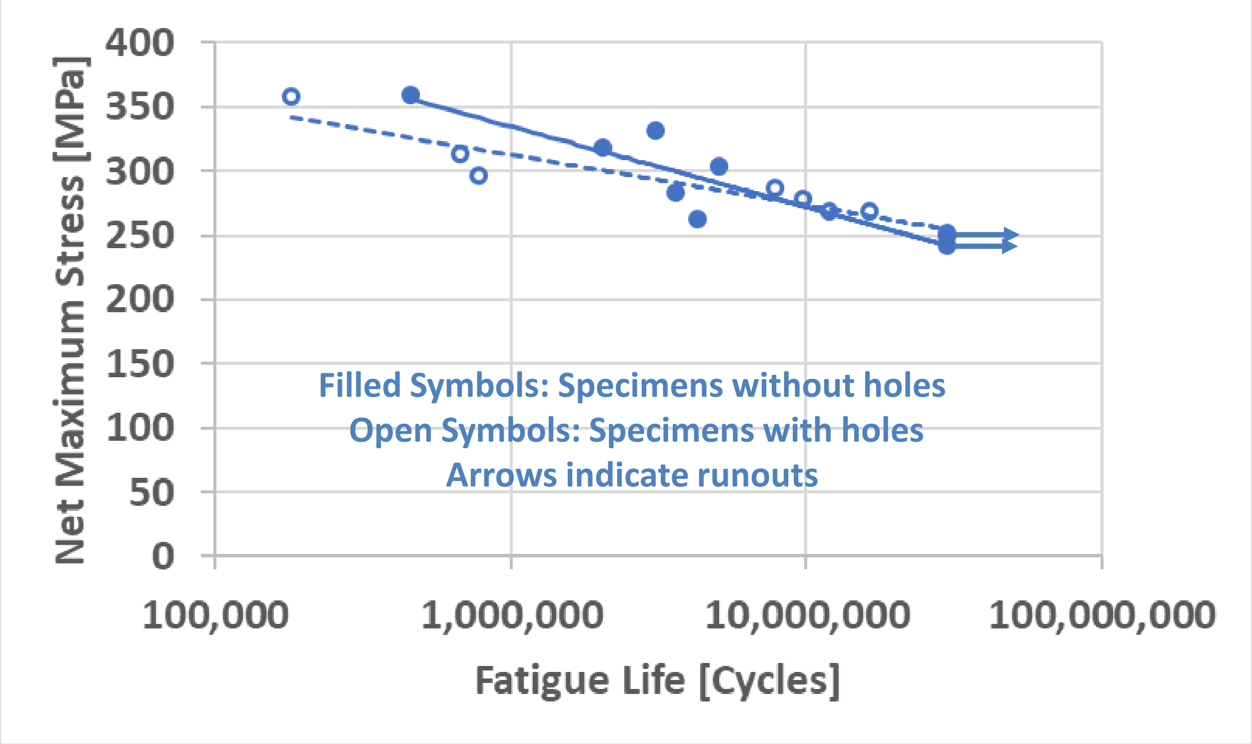
Fractography of HCF Specimen with Simulated Cooling Holes at 1315 °C (2400 °F)



- Samples typically failed at one of the outer cooling holes due to the reduced cross-sectional area
- Holes were within the 25.4 mm gage section (uniform hot zone)
- Holes were created by EDM (electrical discharge machining)
- Holes drilled at 20°, with dimension of 0.66 mm diameter

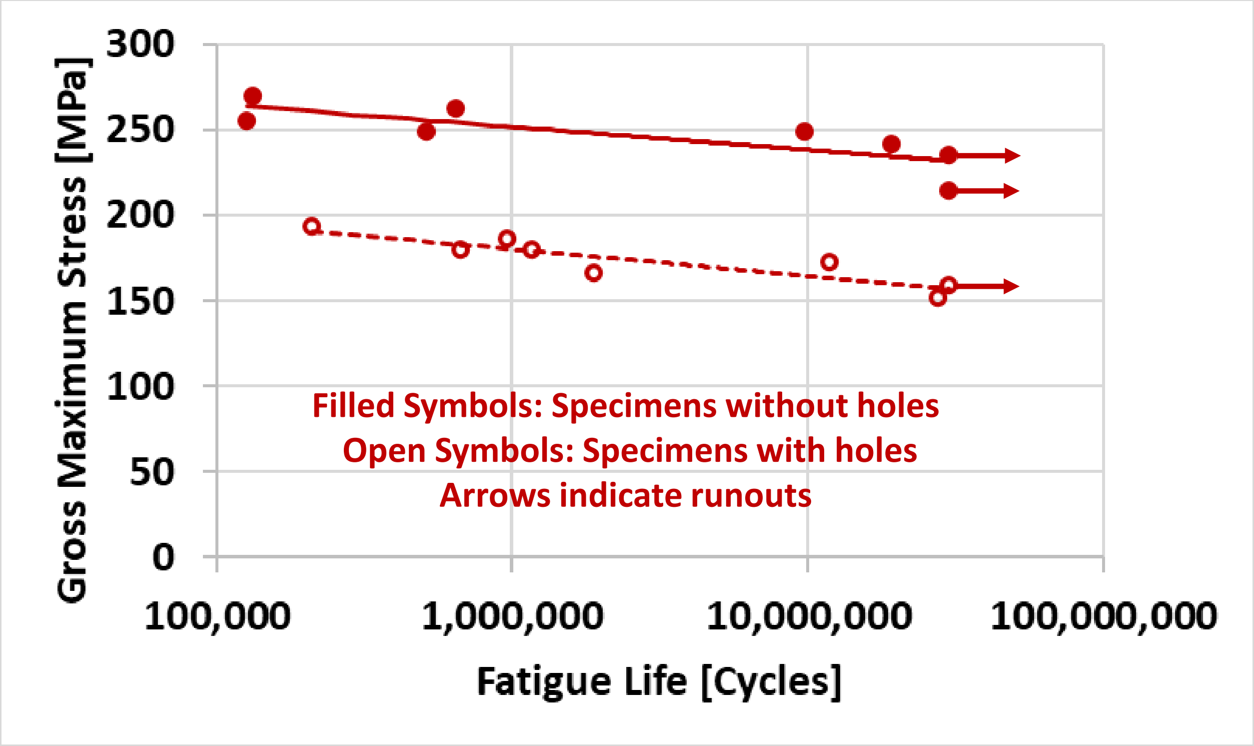
High-Cycle Fatigue (HCF) Behavior without & with Simulated Cooling Holes at 816 °C (1500 °F)

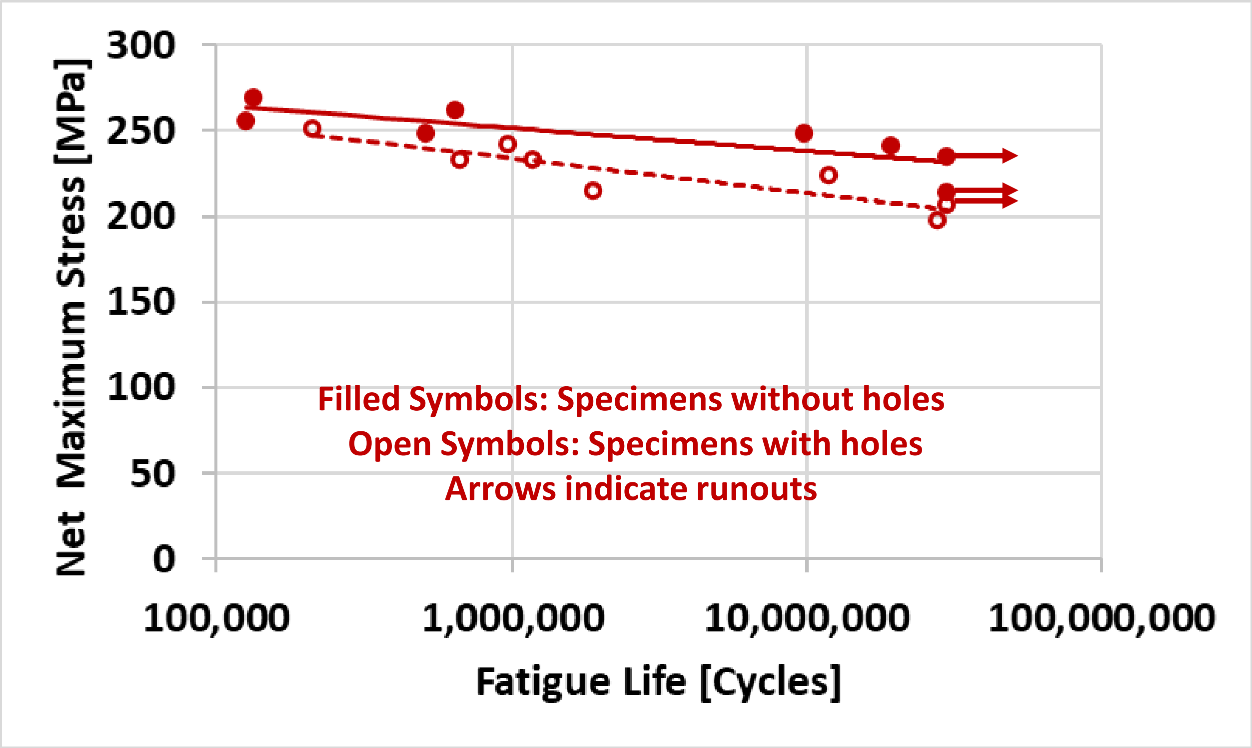




As expected, based on gross stress simulated cooling holes reduced HCF durability at 816 °C (1500 °F). However, only a small effect is observed with net section stress

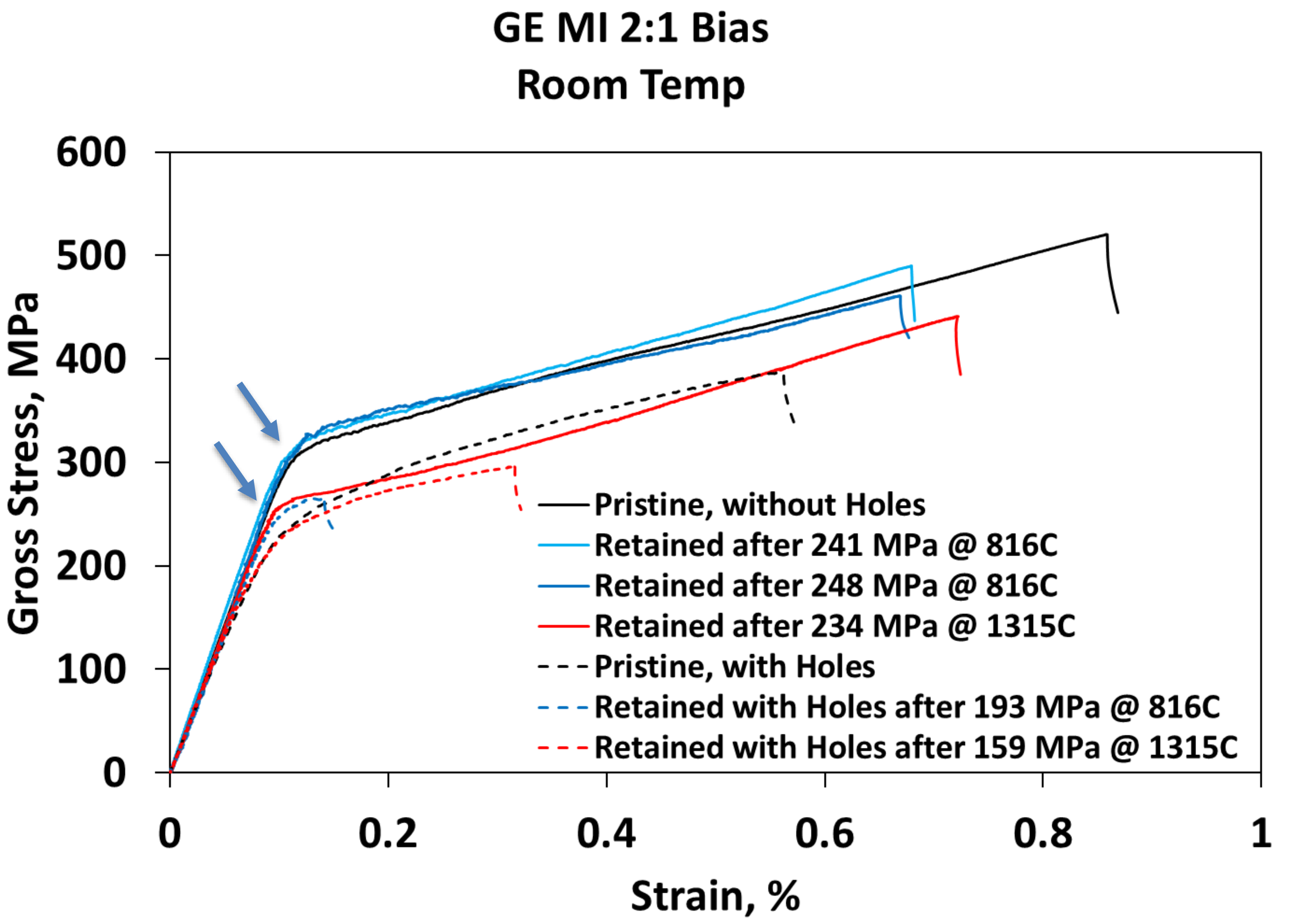
High-Cycle Fatigue (HCF) Behavior without & with Simulated Cooling Holes at 1315 °C (2400 °F)





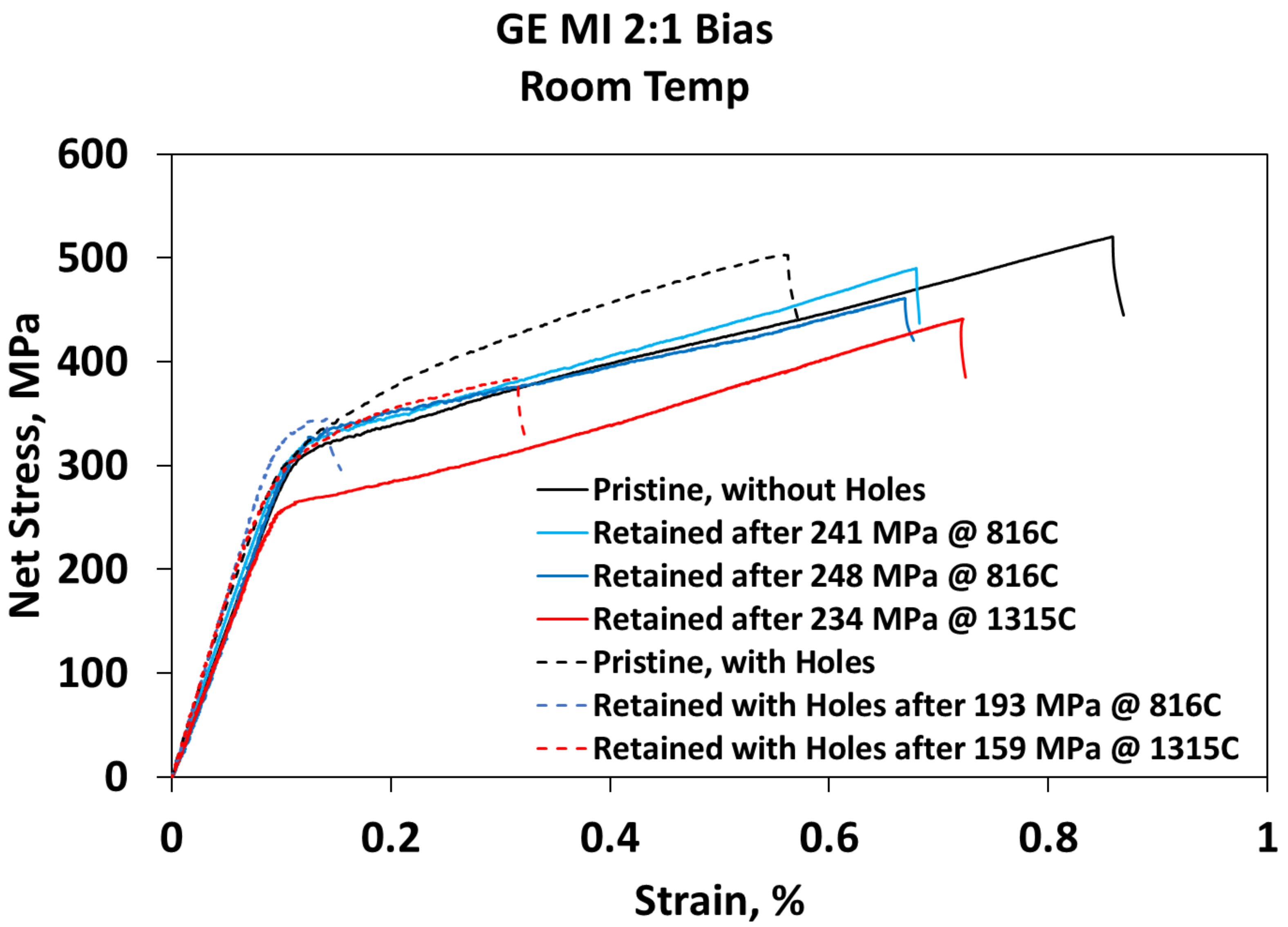
Based on gross stress simulated cooling holes reduced HCF durability at 1315 °C (2400 °F). Reduction in fatigue life is evident even when accounting for net section stress

Room Temperature Baseline (Pristine) & Residual Tensile Strength Tests on Specimens without and with Holes



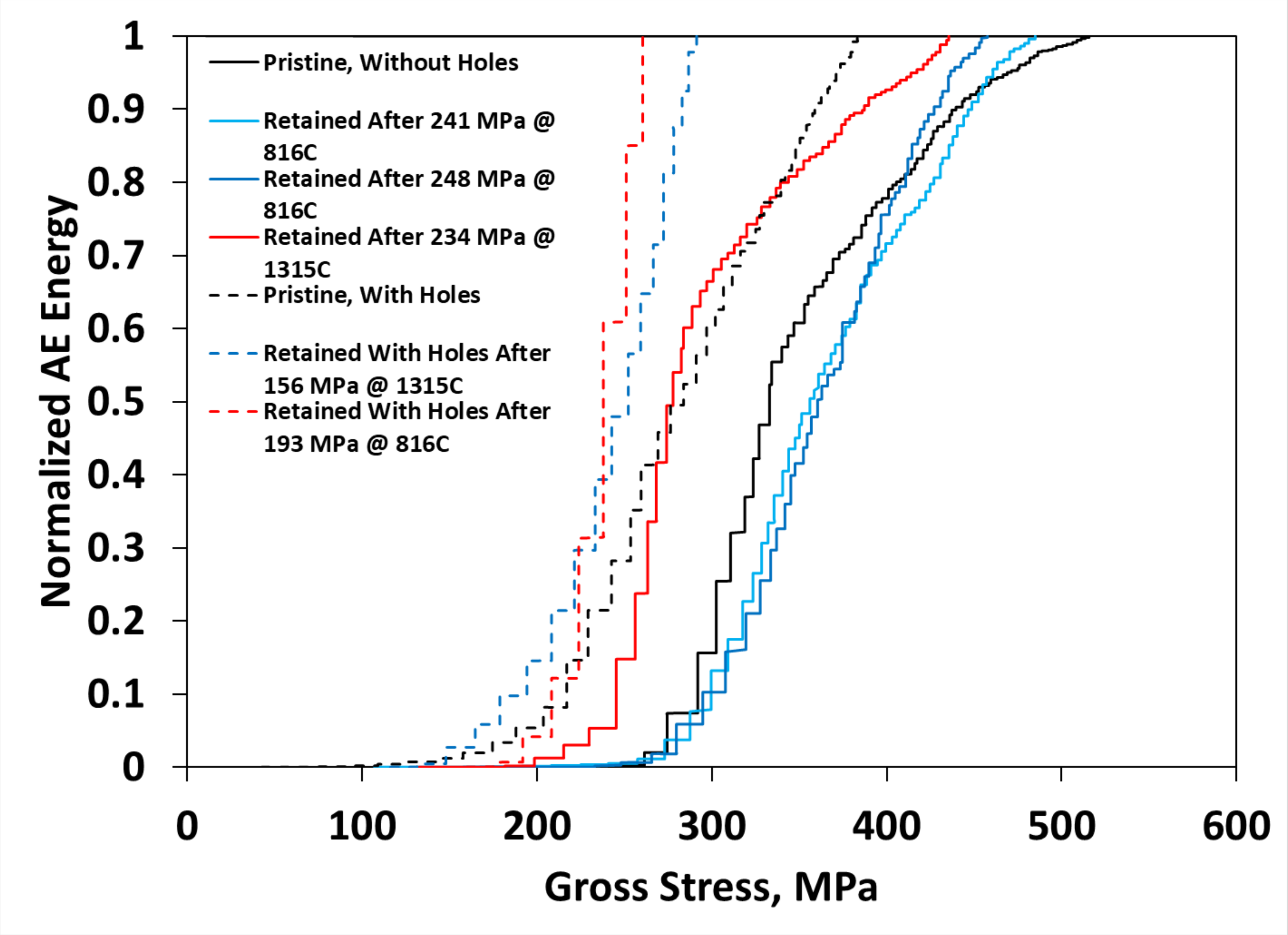
- As expected, on a gross stress basis, proportional limit strength (PLS) values of specimens with simulated cooling holes (baseline and retained strength) are lower

Room Temperature Baseline (Pristine) & Residual Tensile Strength Tests on Specimens without and with Holes



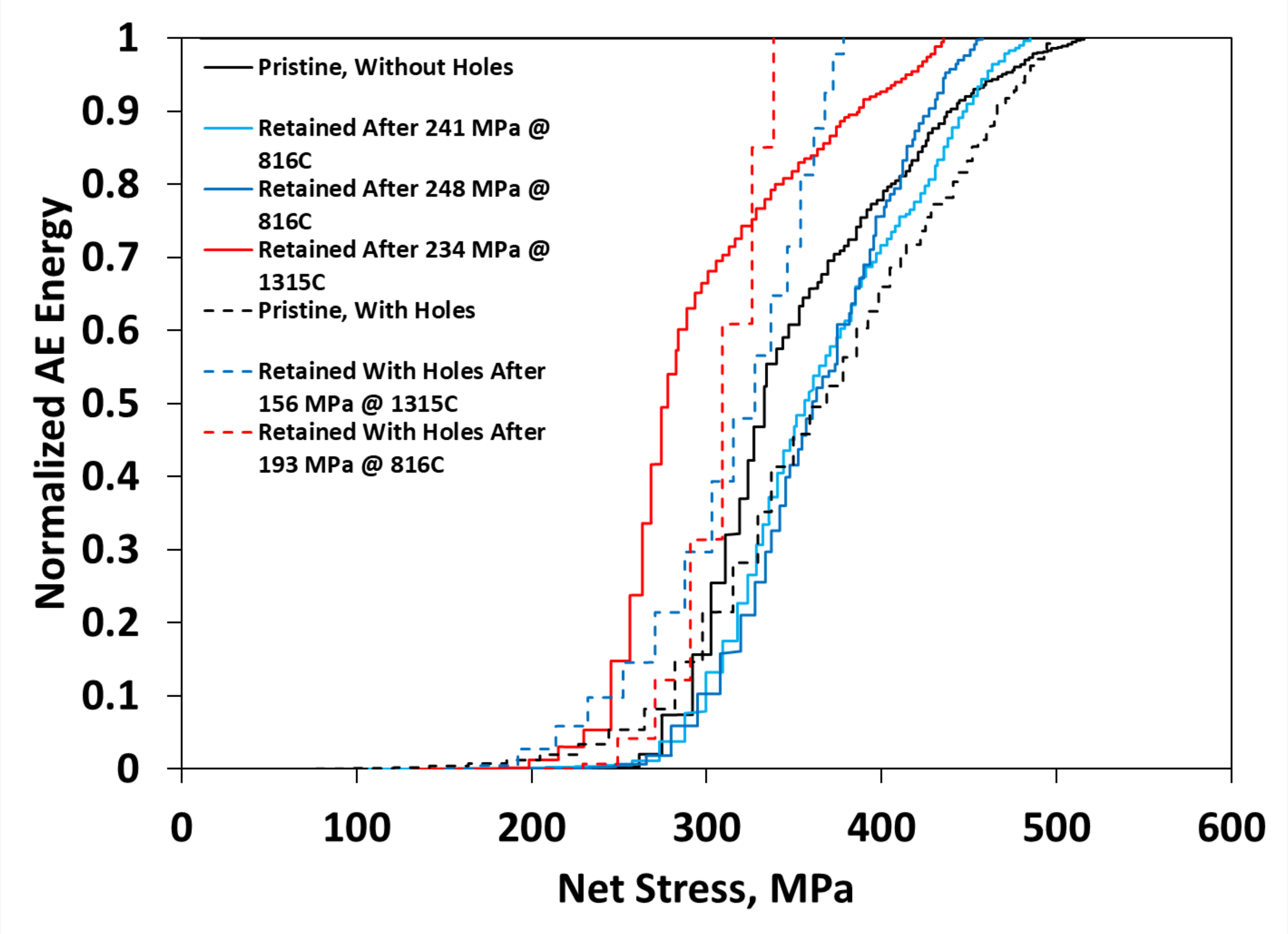
- On net-section stress basis, proportional limit strength (PLS) values of most specimens (baseline and retained strength) are similar
- However, the retained PLS value of the 1315 °C runout specimen without holes tested is much lower
- Lower retained in-plane tensile strength values observed for runout specimens with and without holes indicate damage due to HCF

Room Temperature Baseline & Residual Tensile Strength Tests on Specimens without and with Holes



- **On a gross stress basis, onset of acoustic events appears to occur at lower stresses in specimens with simulated cooling holes**

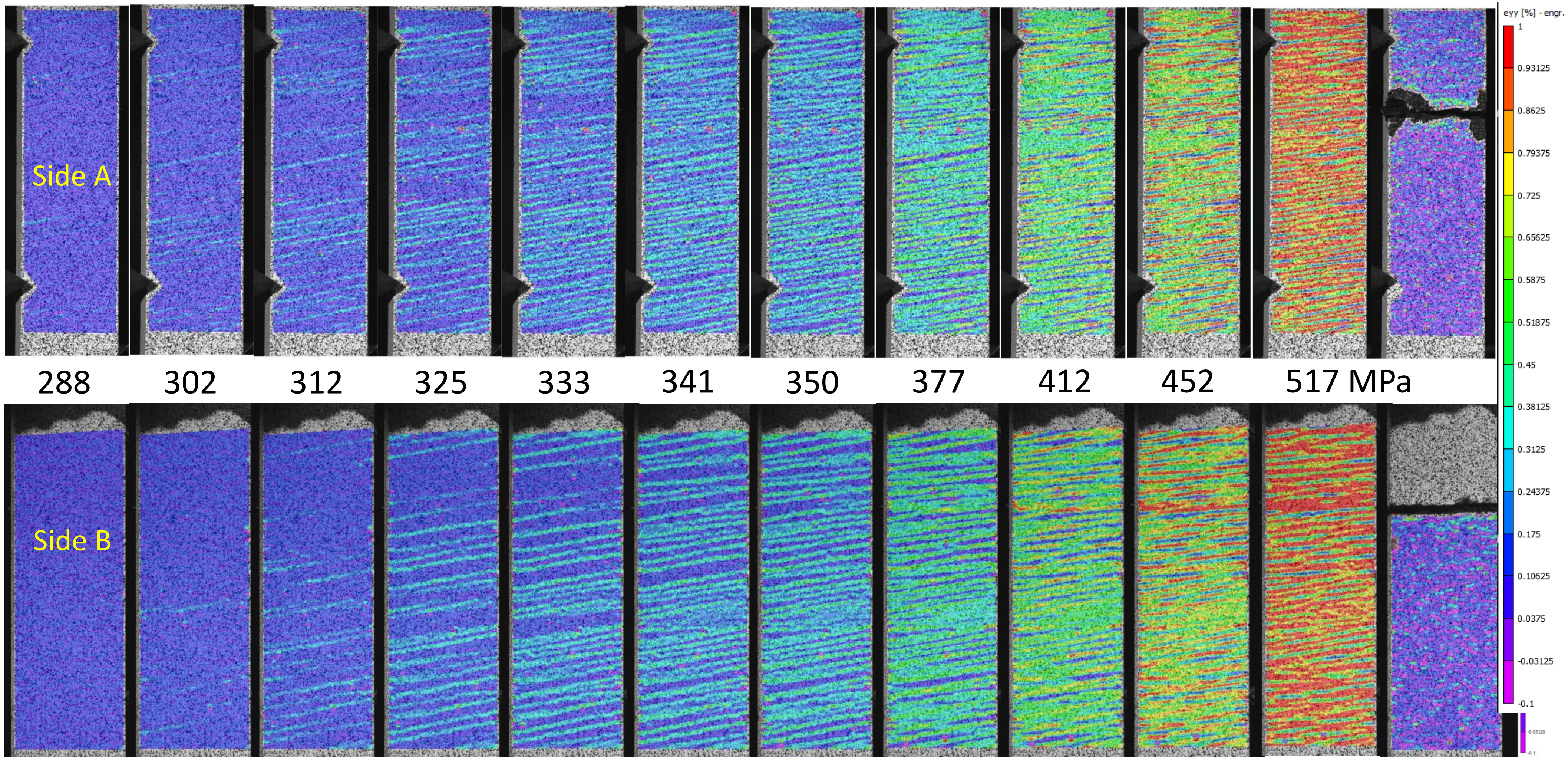
Room Temperature Baseline & Residual Tensile Strength Tests on Specimens without and with Holes



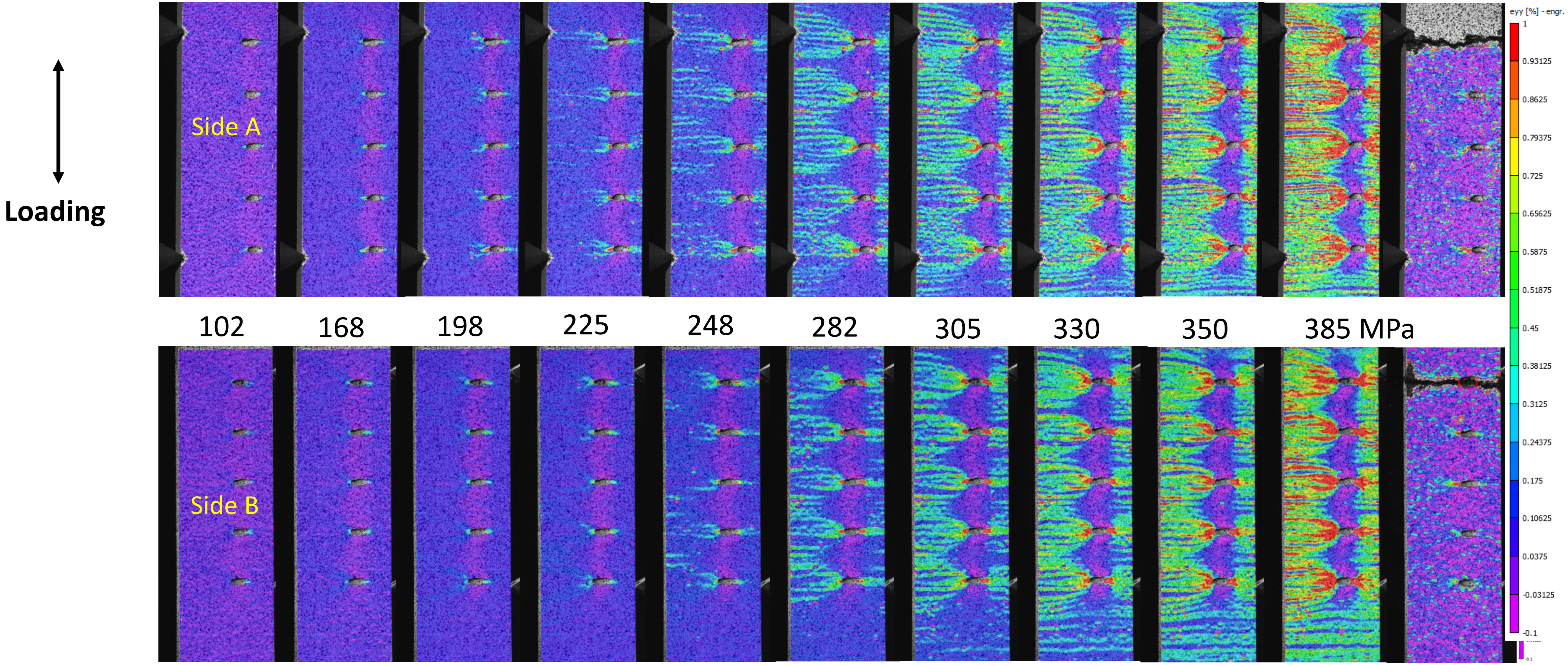
- When compared on a net section stress basis, differences in the stress levels triggering onset of acoustic events diminishes between specimens without and with simulated cooling holes

Room Temperature Baseline Tensile Strength Test on Specimen without Holes: DIC and Gross Stresses (MPa)

Loading

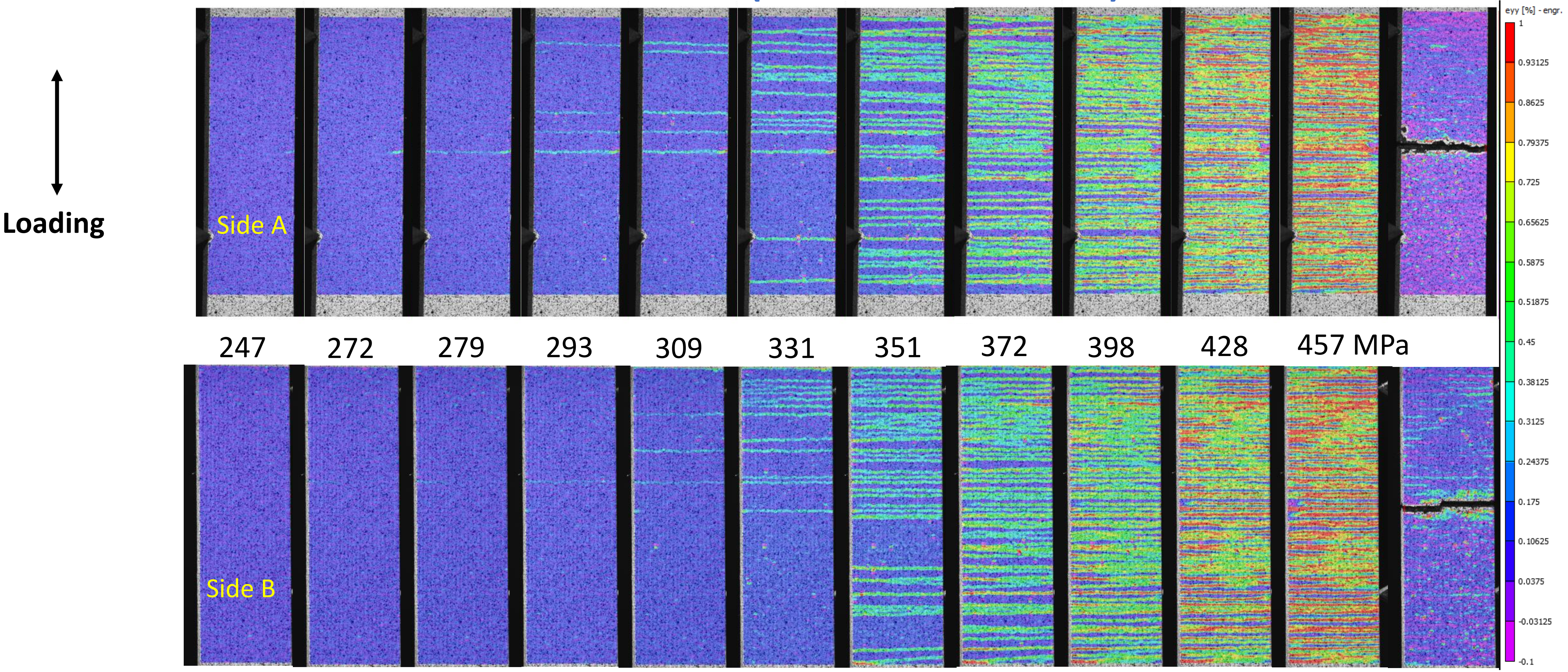


Room Temperature Baseline Tensile Strength Test on Specimen with Holes: DIC and Gross Stresses (MPa)



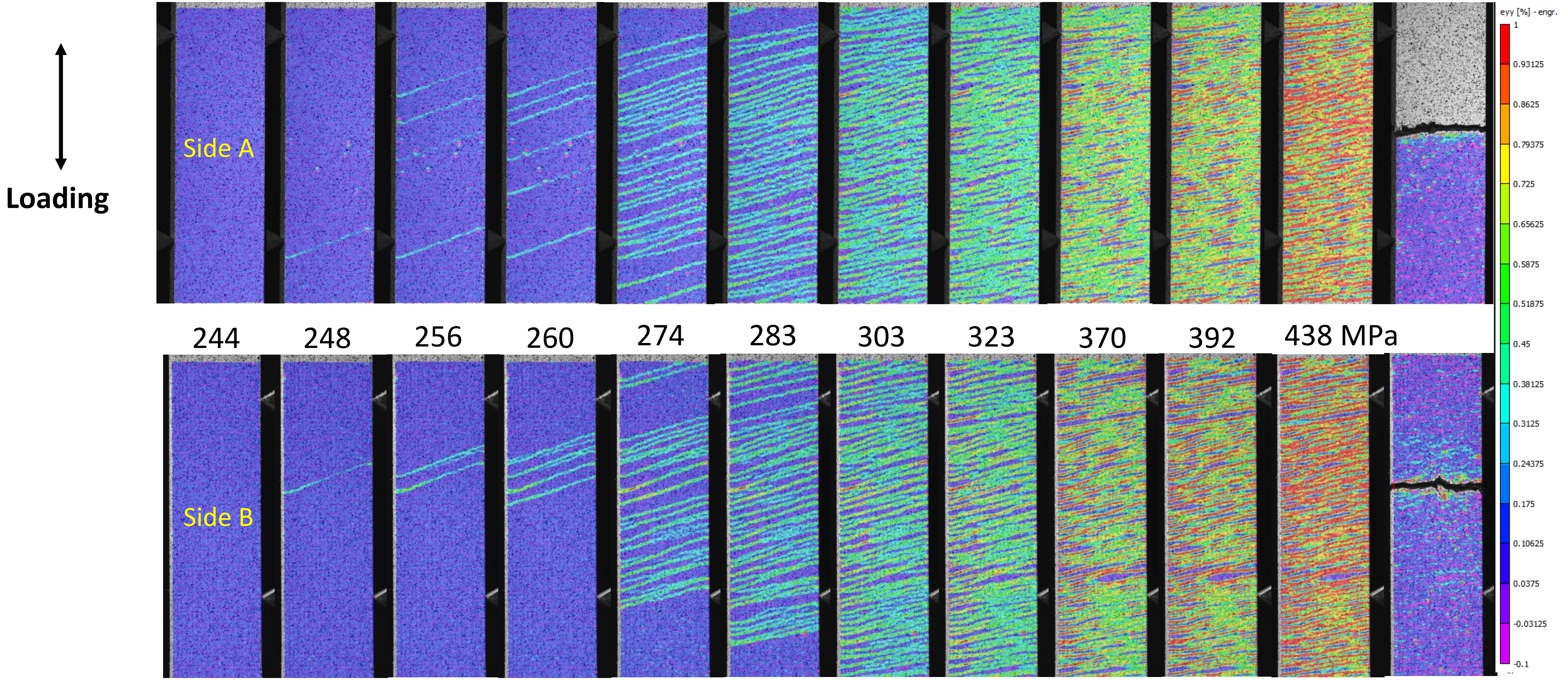
Room Temperature Retained Tensile Strength Test on Specimen without Holes: DIC and Gross Stresses (MPa)

HCF Runout (248 MPa and 816 °C)



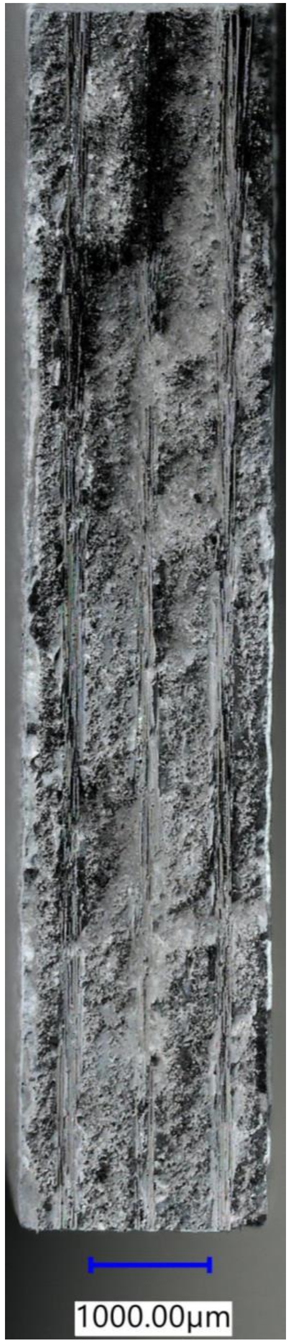
Room Temperature Retained Tensile Strength Test on Specimen without Holes: DIC and Gross Stresses (MPa)

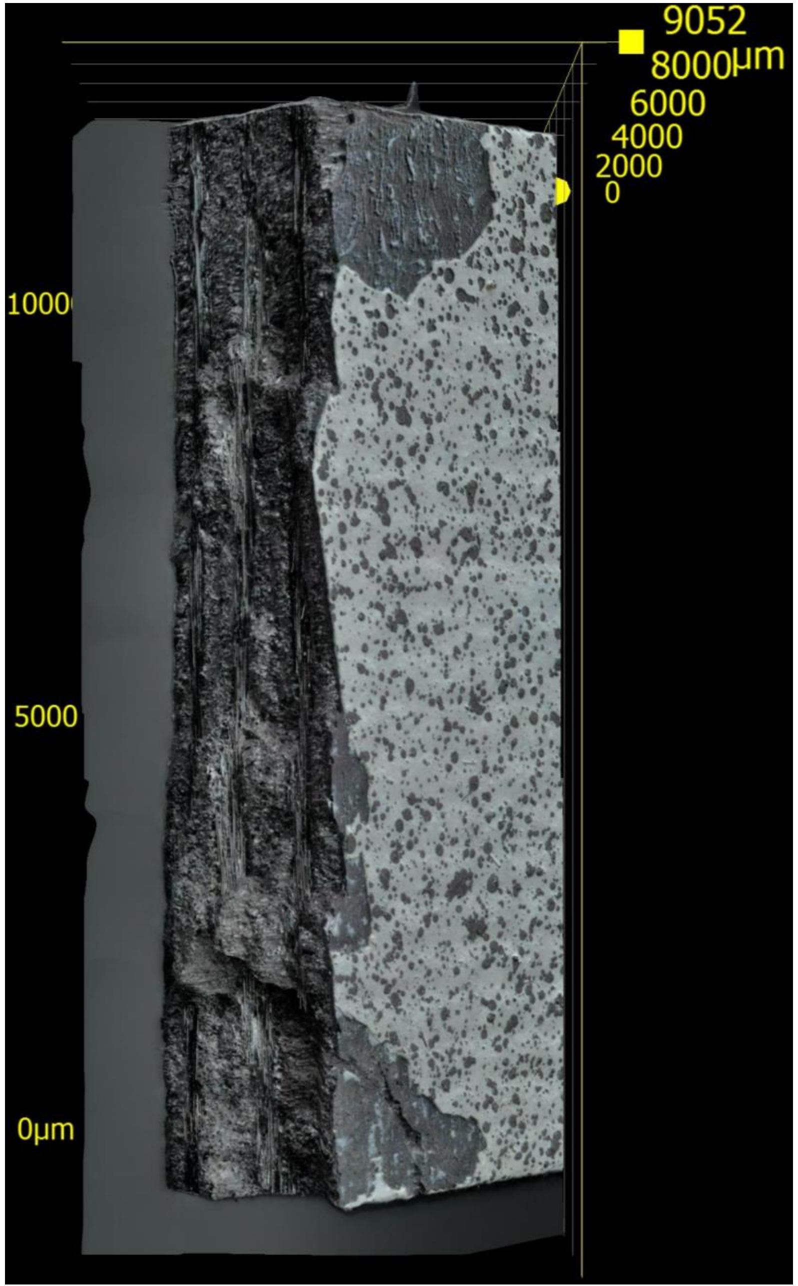
HCF Runout (234 MPa and 1315 °C)



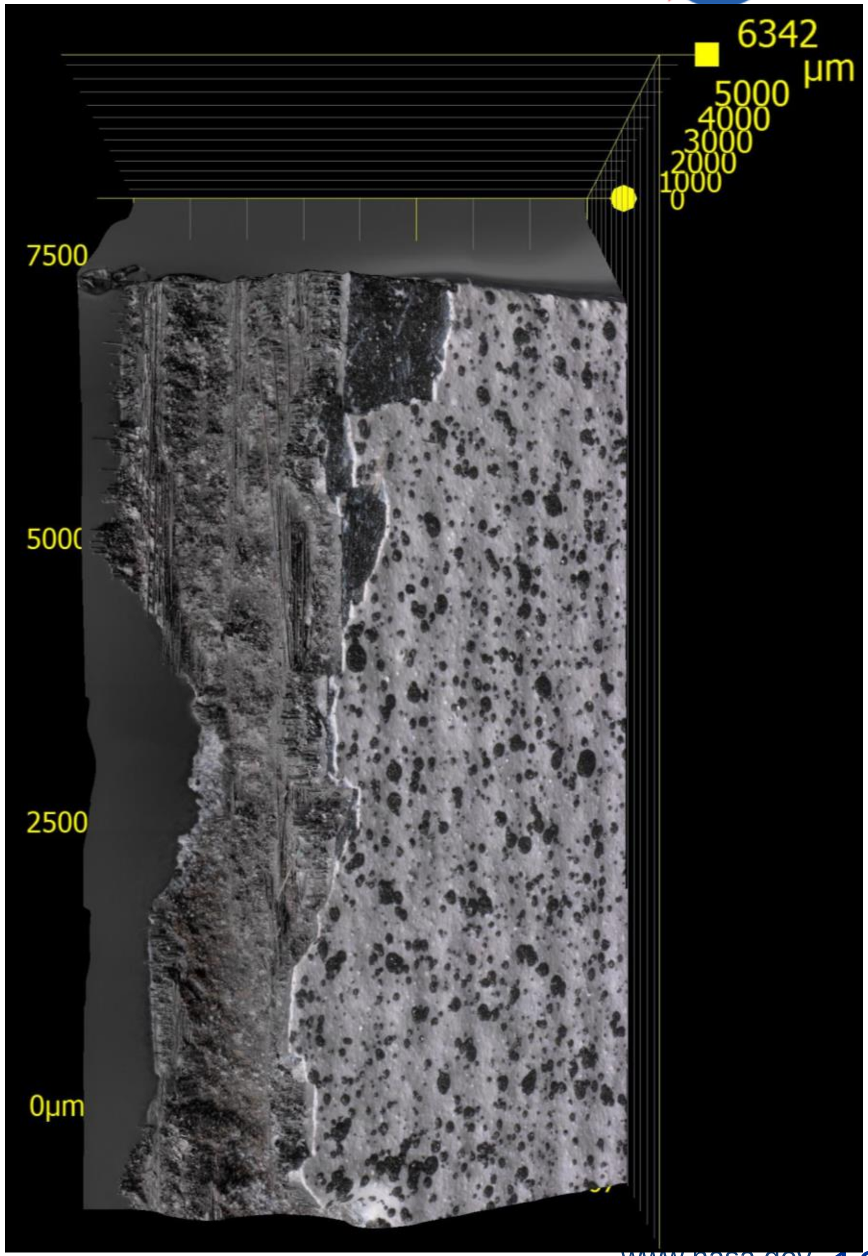
2D and 3D Optical Images of Fracture Surfaces

Pristine without holes



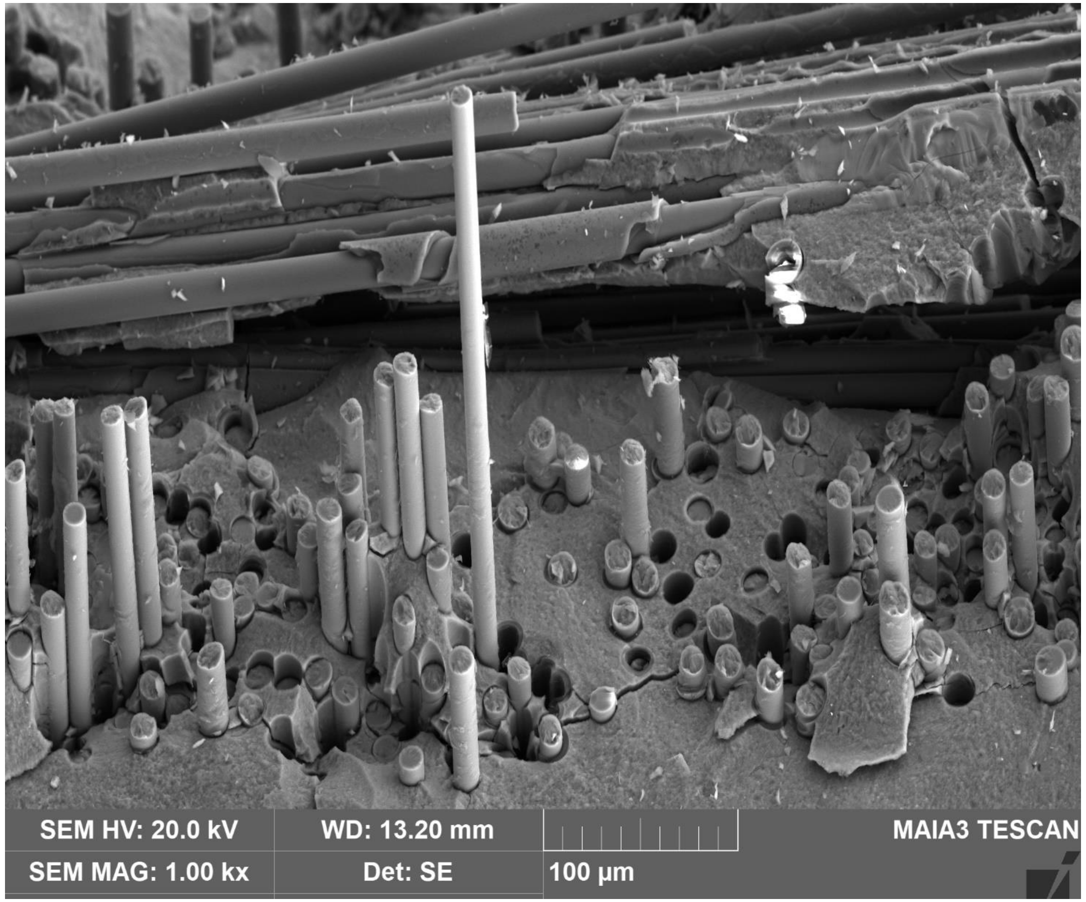


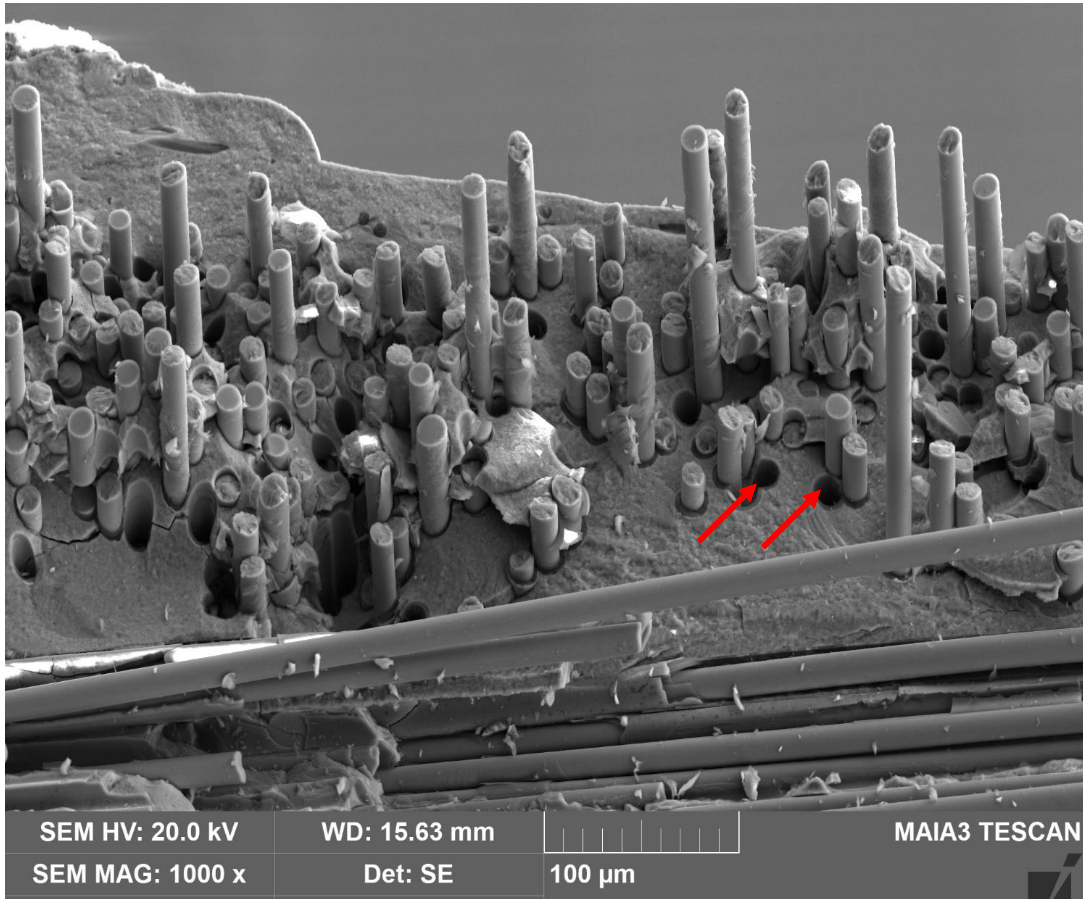
Pristine with holes



Fractography of HCF Specimen without Simulated Cooling Holes at 24°C (75°F)

14950-TD-5 Room Temperature Fast Fracture

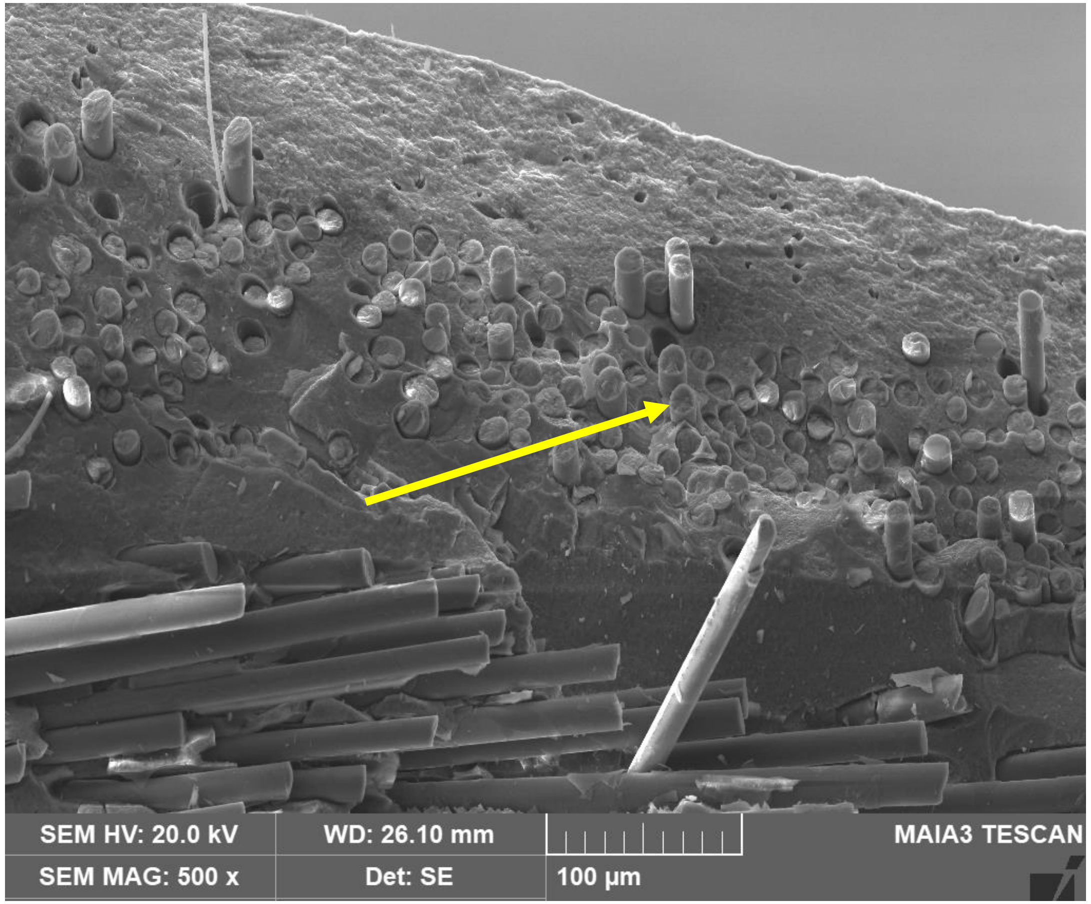




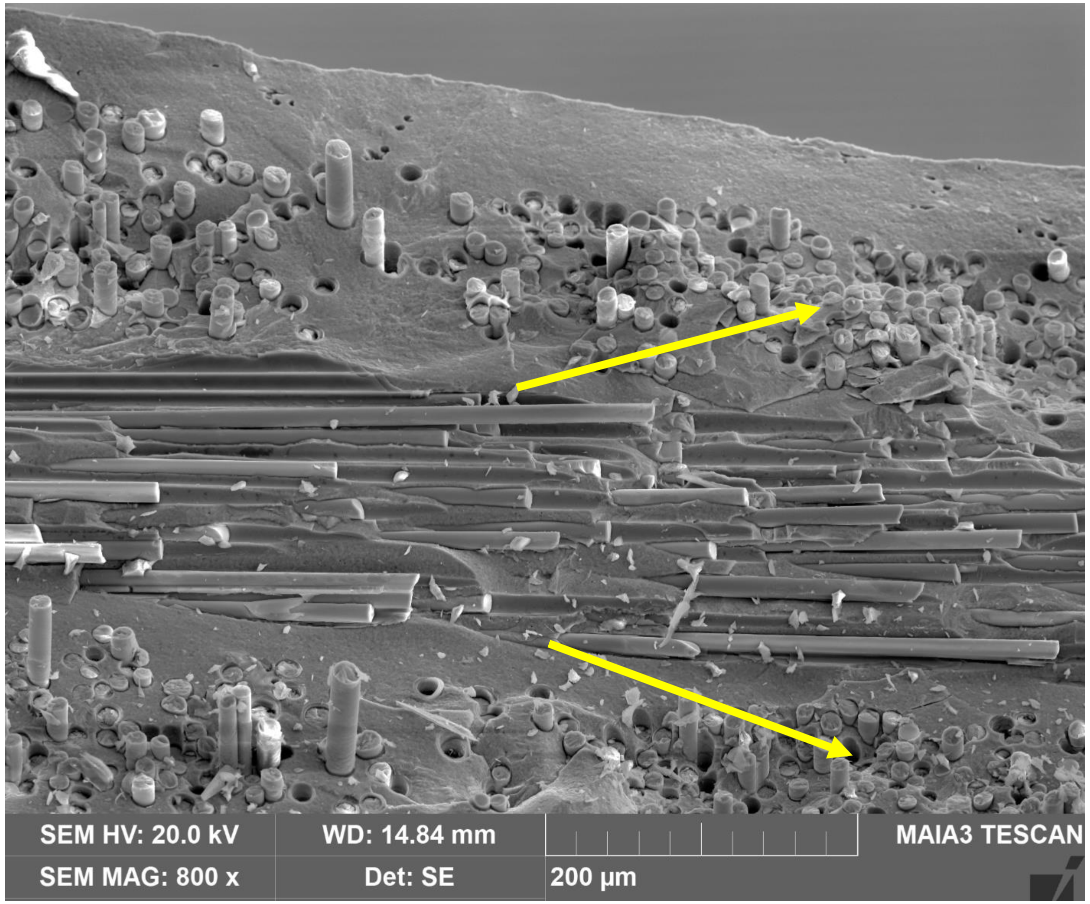
- **Significant fiber pullout observed throughout the sample**
- **See holes where fibers have pulled out (red arrows)**

Fractography of HCF Specimen without Simulated Cooling Holes at 816°C (1500°F)

14946-TD-4   816°C   317 MPa   19 hr



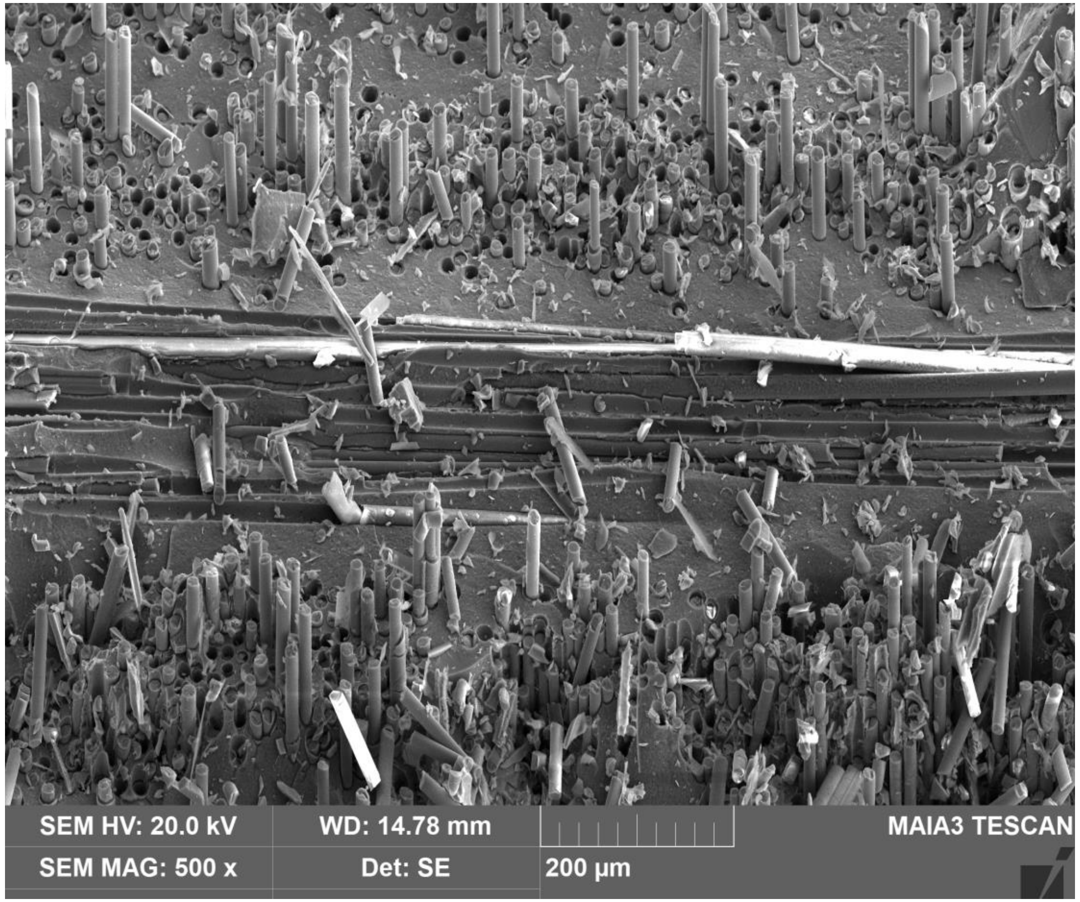
14950-TD-1   816°C   359 MPa   4.3 hr

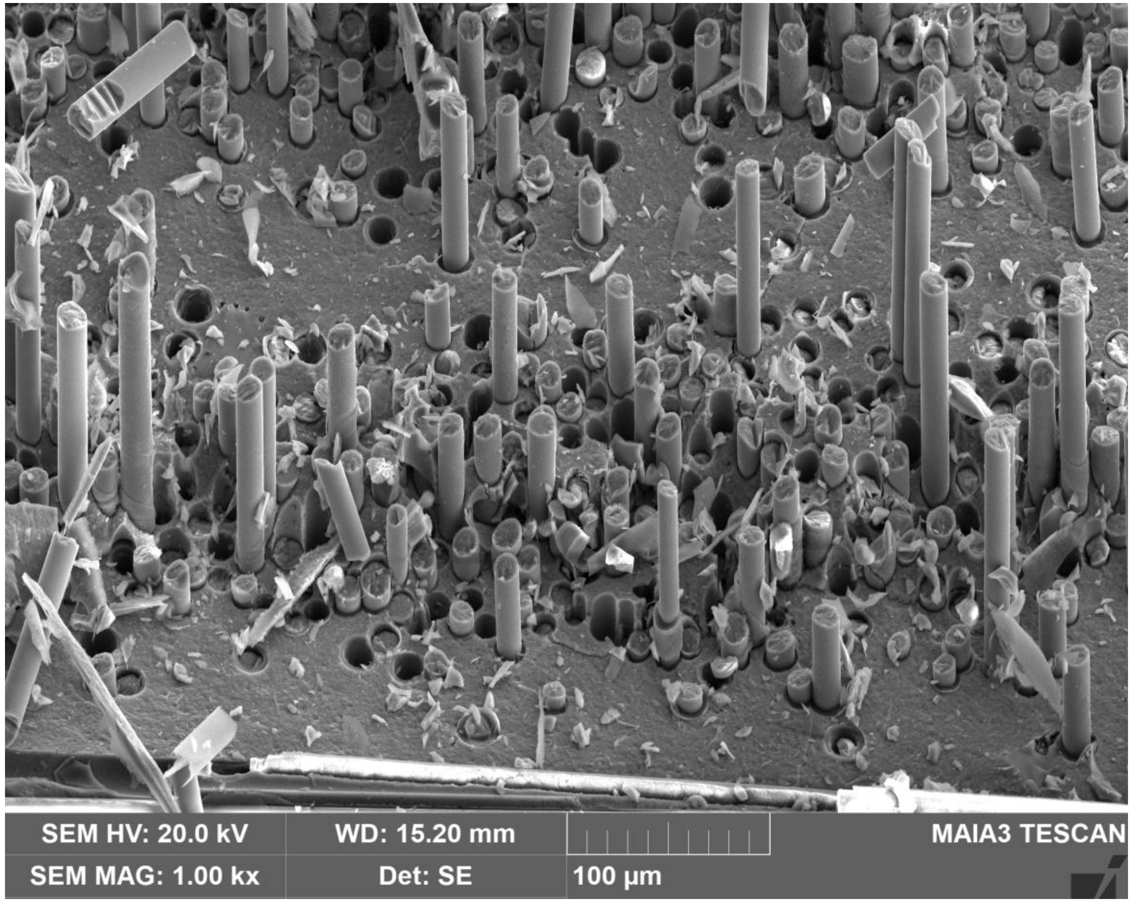


- **Regions of "limited fiber pull-out" observed (yellow arrows)**
- **Some 0° plies exhibited embrittlement**

Fractography of HCF Specimen without Simulated Cooling Holes at 1315°C (2400°F)

14951-TD-1   1315°C   241 MPa   179 hr

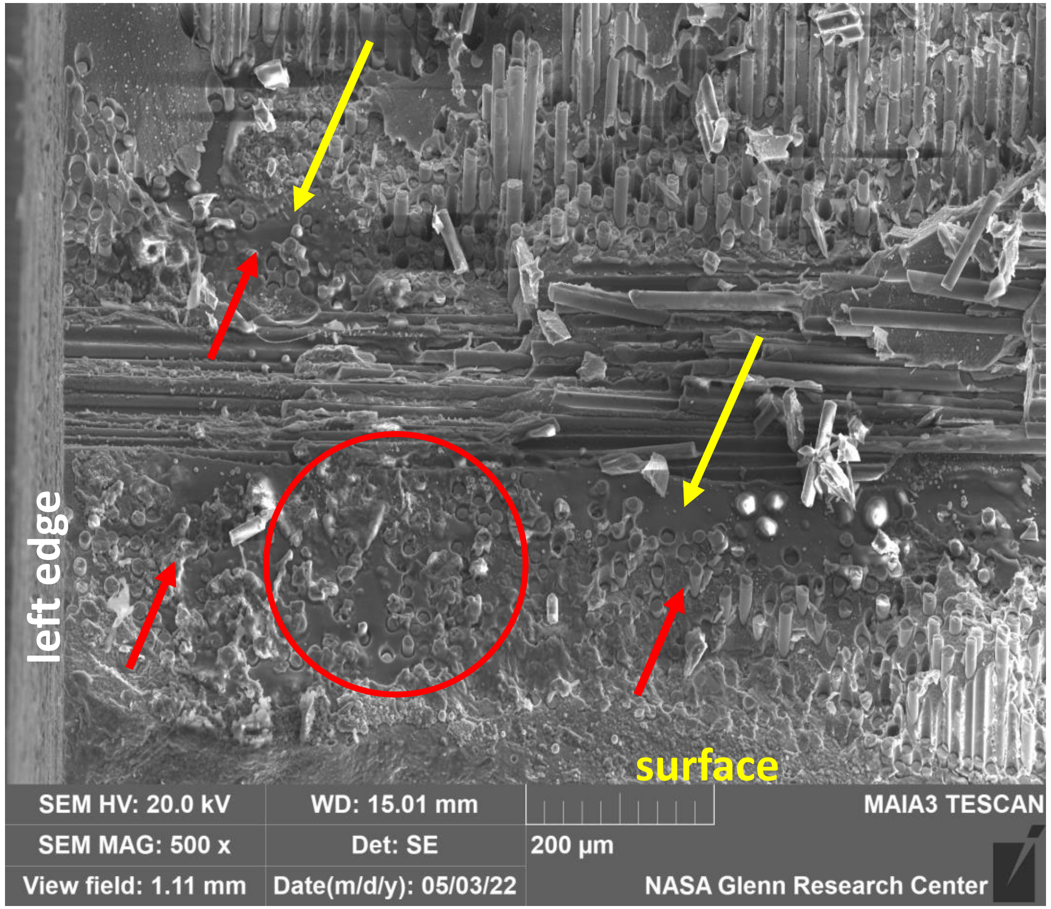


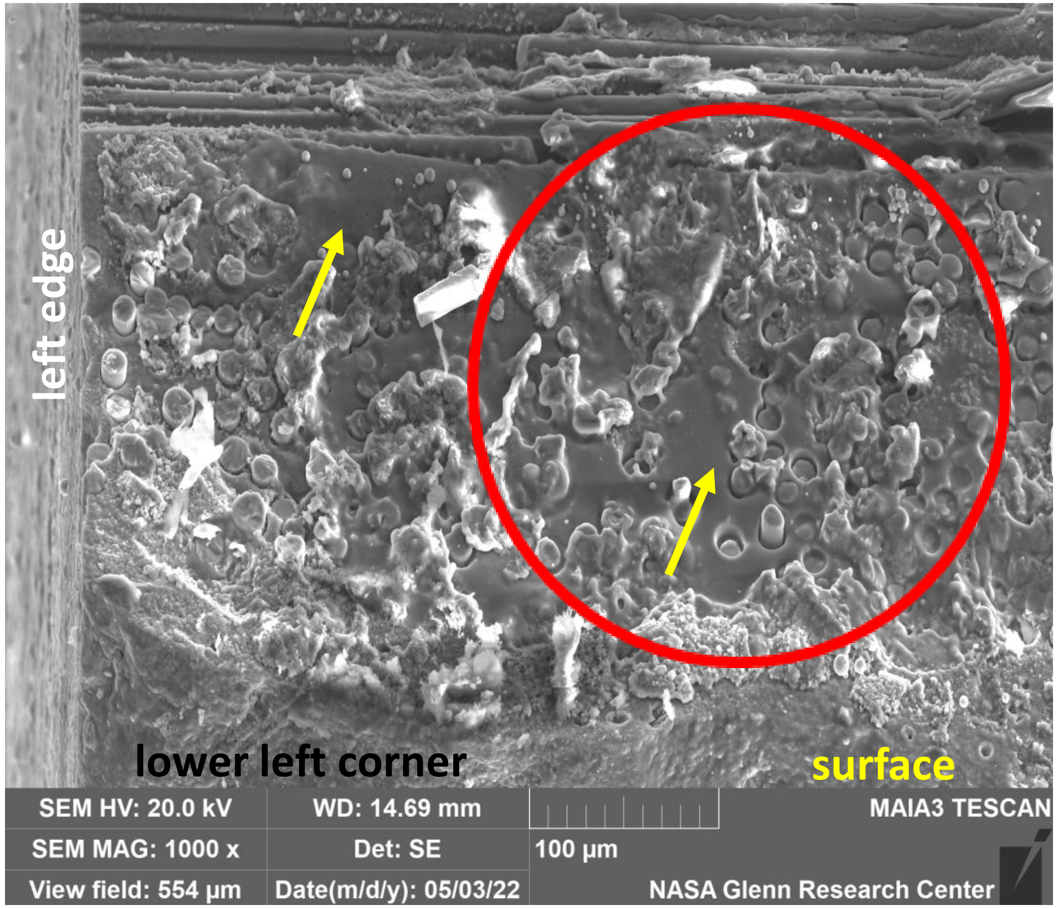


- **Interior: Fairly significant fiber pull-out observed at 500 and 1000X**
- **Failure occurred due to oxidation and embrittlement in other areas.**

Fractography of HCF Specimen without Simulated Cooling Holes at 1315°C (2400°F)

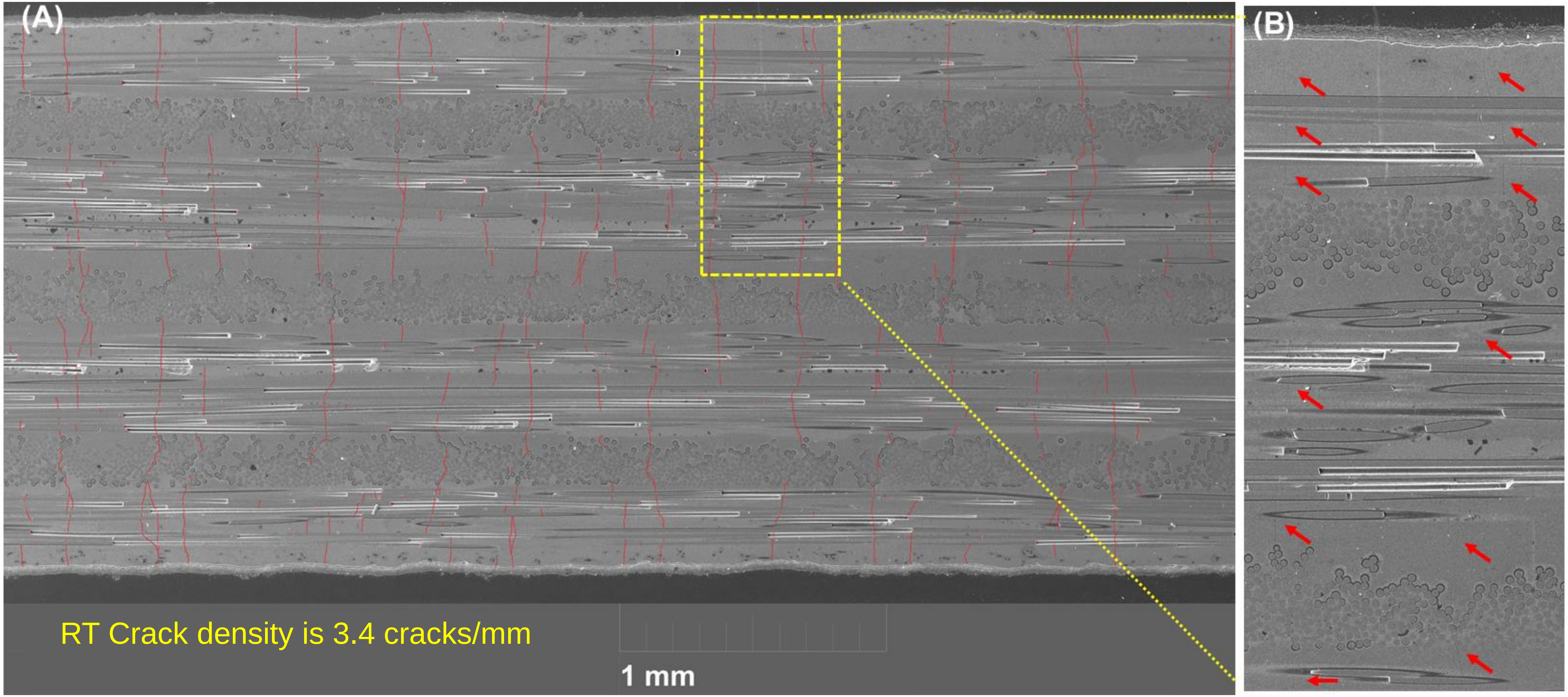
14951-TD-3 1315°C 248 MPa 4.7 hr





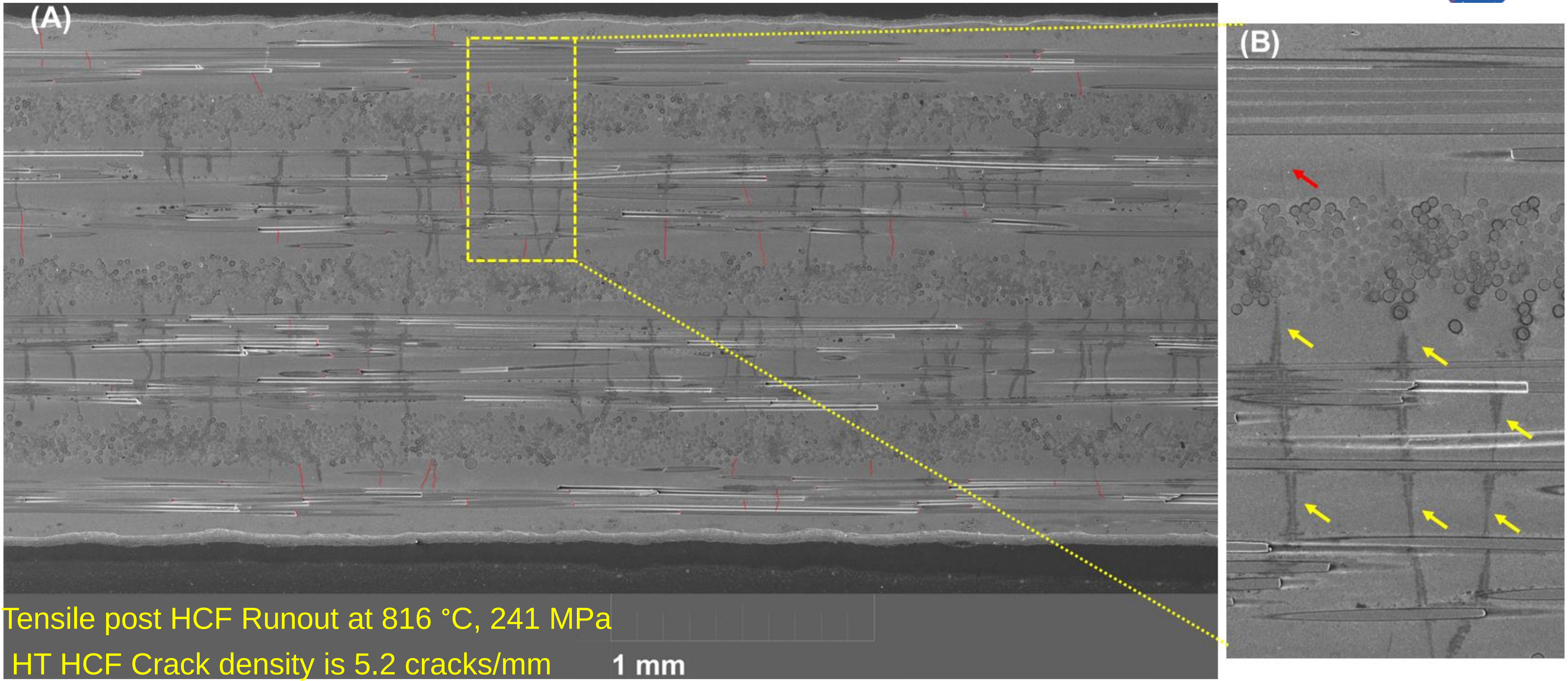
- **Lower left corner: Embrittled regions observed where 0° fibers have broken off (red circle & arrows)**
- **Note smooth regions (yellow arrows) which appear glassy (oxide formed) [500 & 1000X]**

Crack Formation During RT Tensile Testing



- Low and high magnification, of polished edge from pristine specimen that was tested in tension at room temperature.
- Initiation and propagation of the room temperature cracks during the tensile test of as-fabricated specimen was a result of increasing applied stress beyond the proportional limit until the sample failed. (# of AE events~ 11134)

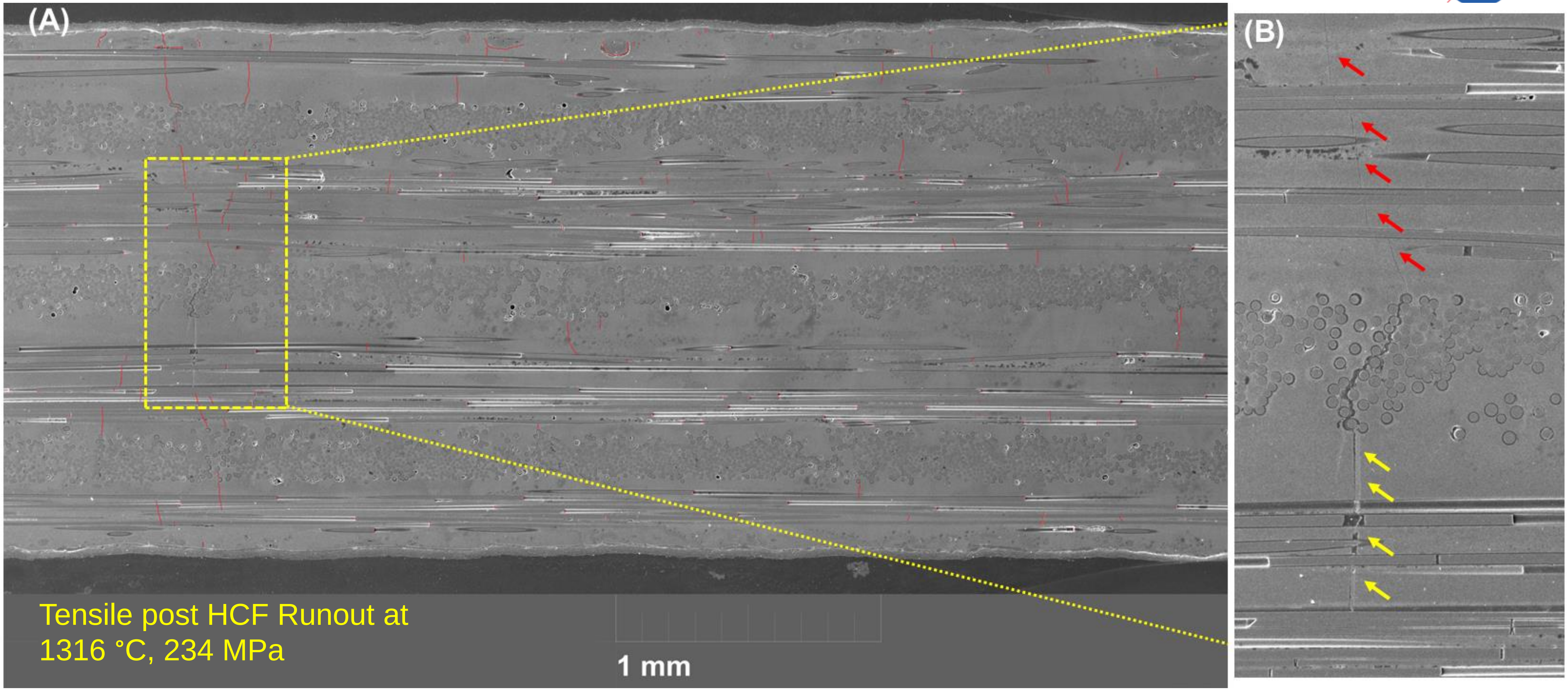
Crack Formation and Oxidation during HCF at 816 °C



-Formation of cracks during the HCF test at 816 °C was a result of cyclic mechanical loading without the presence of relaxation or creep at 816 °C, which prevented the matrix from accommodating the accumulation of cyclic loading-induced strains.

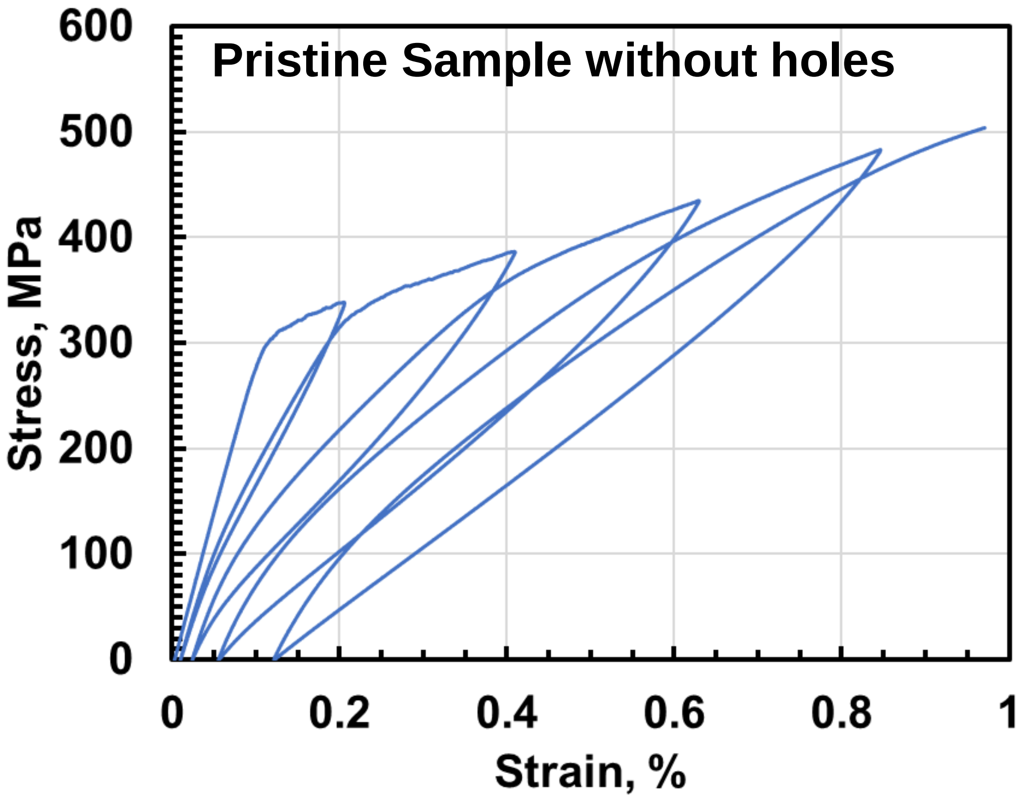
- HT HCF cracks show oxidation damage that is likely due to the formation and flowing/spilling of borosilicate melt in the vicinity of the cracks and subsequent solidification upon cooling to room temperature. (# of AE events~ 8868)

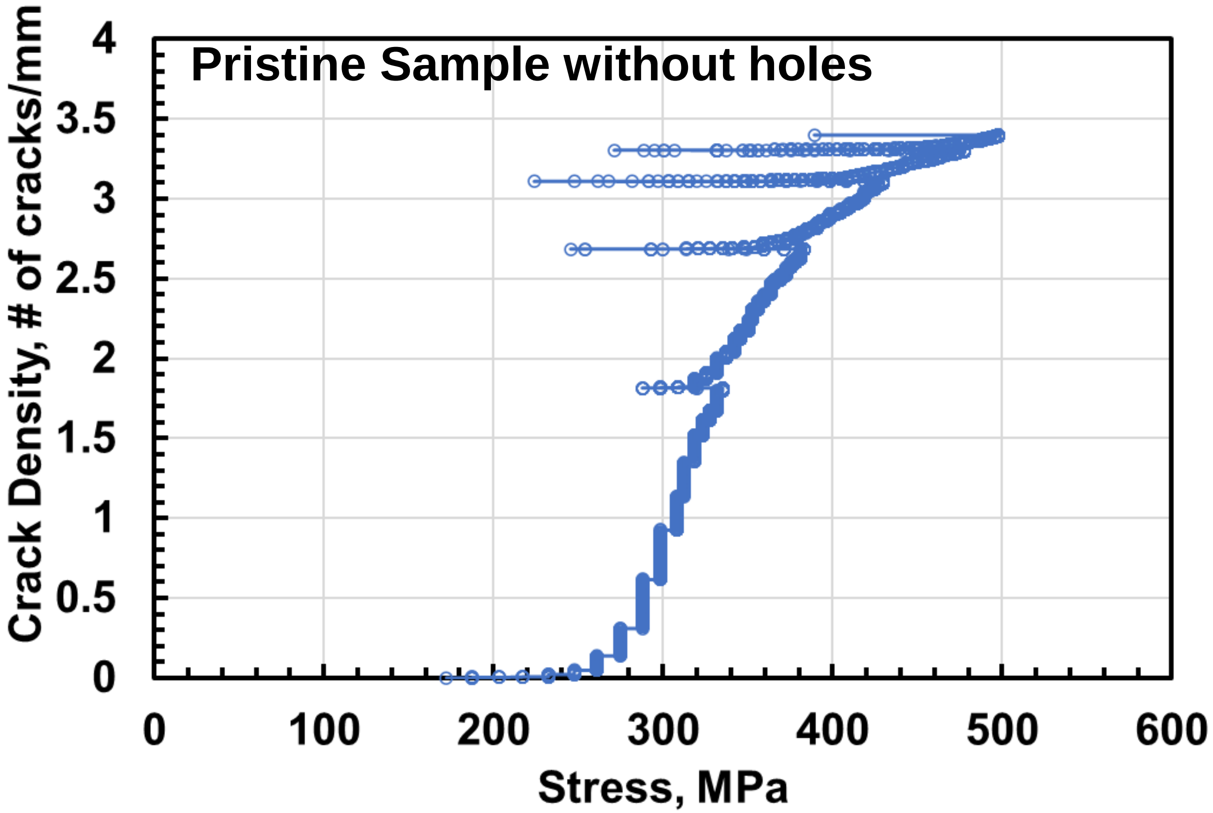
Crack Formation and Oxidation during HCF at 1315 °C



- Lack of HT crack formation in this specimen is likely due to relaxation and creep that occur in SiC based CMCs when mechanically loaded at 1315 °C which allow the matrix to accommodate the accumulation of cyclic loading-induced strains.
- A crack that formed during HCF test at 1315 °C presumably filled with solid borosilicate glass oxide and later propagated during the post runout RT tensile test. (# of AE events~ 9516)

Stress-Dependent Crack Density Evolution Derived from AE

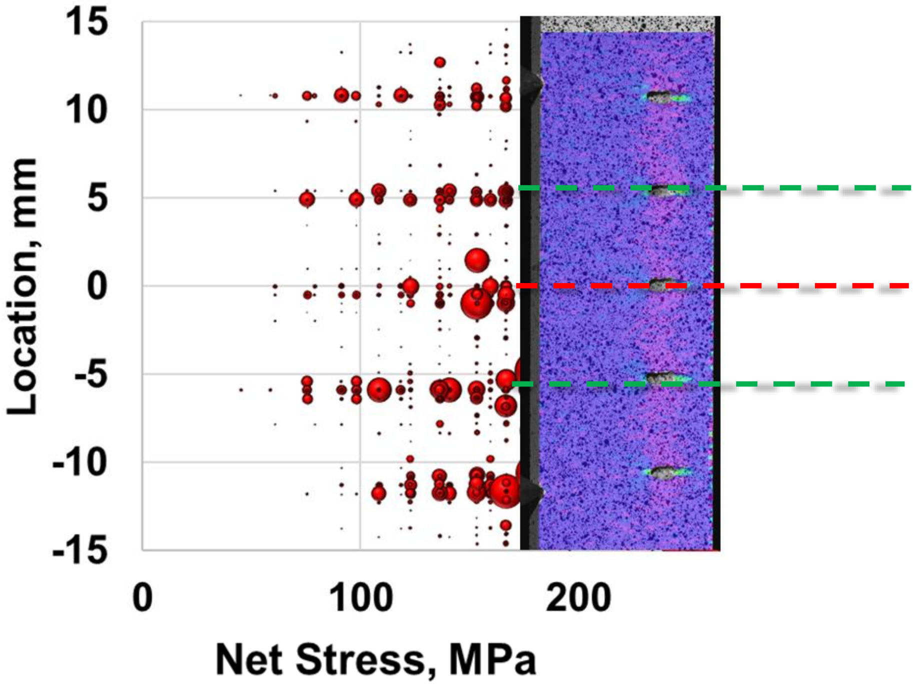


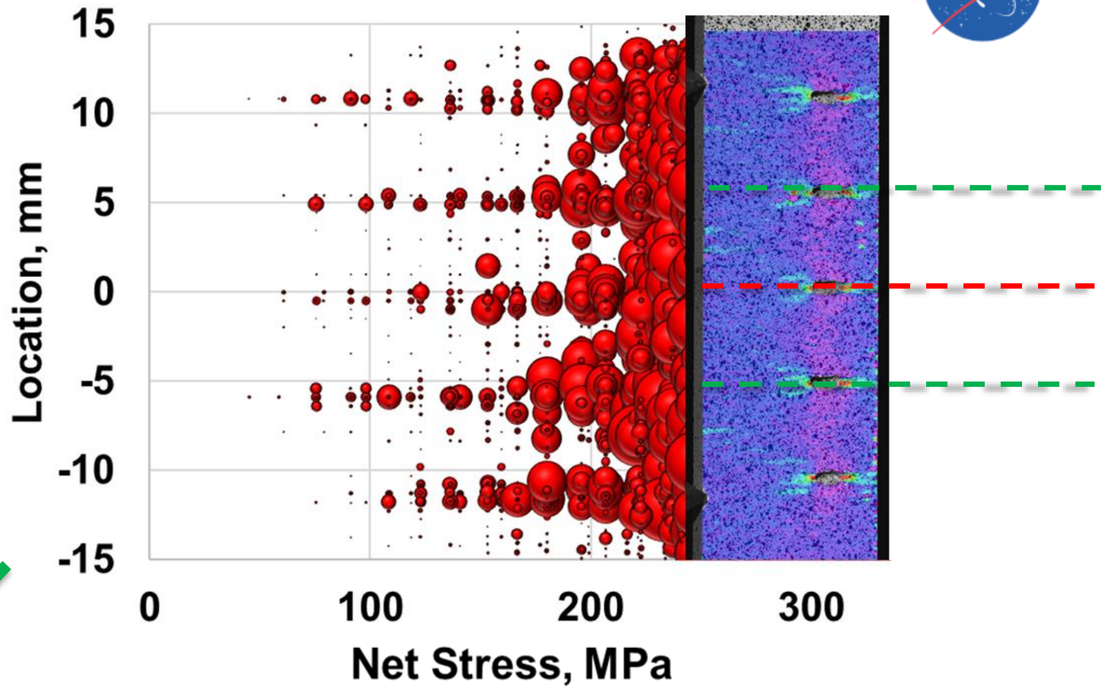


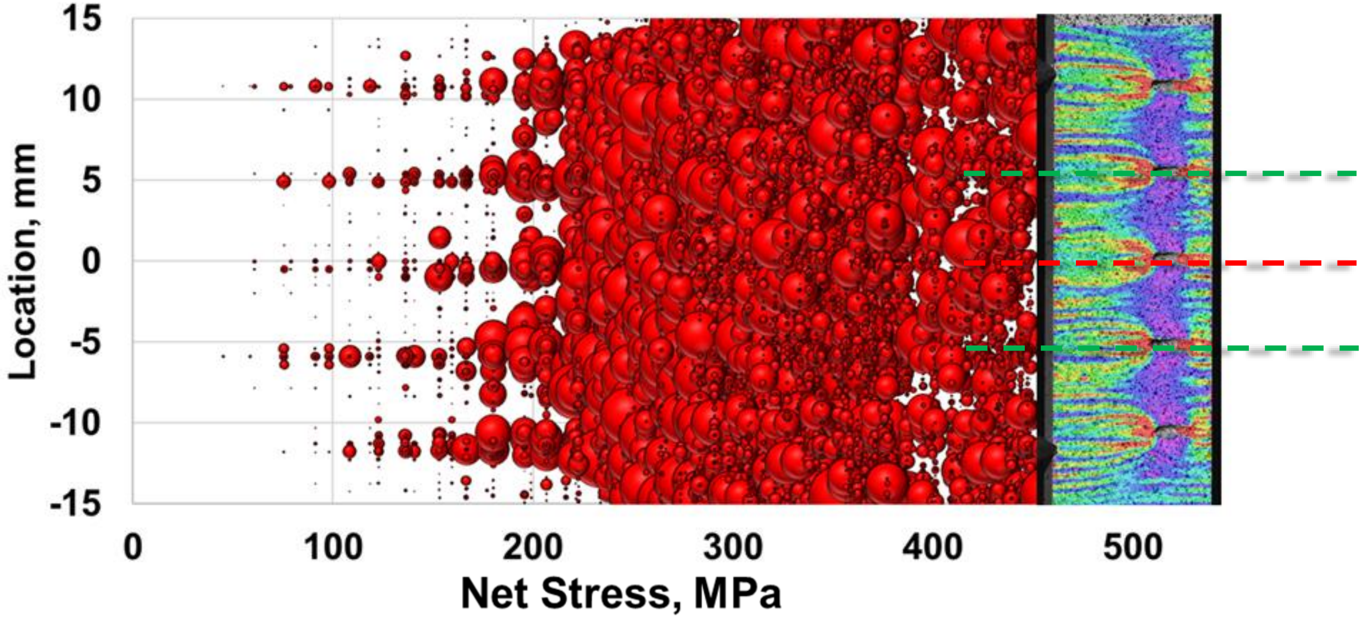
- The normalized cumulative AE energy curve for a pristine sample without holes tested at RT in hysteresis loading to failure was multiplied by the measured crack density at failure to obtain the stress-dependent crack density evolution.

Sample Condition	# of AE Events
Pristine Tensile	11134
HCF Runout at 816 °C, 241 MPa then Tensile at RT	8868
HCF Runout at 1316 °C, 234 MPa then Tensile at RT	9516

Correlation between AE Location and DIC







Good agreement between AE Location and DIC in pristine sample with holes, especially at cracking onset and initiation.

Summary

- ❑ **On a net-section stress basis:**
- ✓ **Proportional limit strength (PLS) and in-plane tensile strength (ITS) strength values for both types of specimens are somewhat similar.**
- ✓ **HCF lives of specimens with holes are somewhat lower than that of specimens without holes; more so at 1315 °C than at 816 °C. This might be due to cyclic creep and oxidation within cracks formed during HCF at the higher temperature.**
- ✓ **Retained tensile strengths of runout HCF specimens without and with simulated cooling are similar with one exception (PLS value of the runout specimen without holes tested in HCF at 1315 °C).**
- ✓ **Lower retained ITS values observed for runout specimens with and without holes indicate damage due to HCF.**
- ❑ **Fractography: HCF CMC specimens tested at 816 °C exhibited embrittled regions where oxidation prevented 0° fiber pull-out. At 1315 °C, smooth glassy phase was observed in areas where degrading oxidation had occurred (this was not observed at 816 °C). In other regions, significant fiber pull-out and embrittled regions with fiber breakage were observed at 1315 °C**
- ❑ **Acoustic emission results provided early detection of cracking in the CMC in room temperature tensile tests and served as an alternative means to obtain PLS values in addition to conventional stress-strain curves in tensile strength tests.**
- ❑ **Crack formation and propagation at room and high temperature were discussed and crack densities were measured.**
- ❑ **AE was used to estimate the stress dependent crack density evolution at RT.**
- ❑ **Digital image correlation was able to identify high strain regions in the vicinity of the simulated cooling holes early in the tensile tests and tracked the damage as the load increased. DIC results also served as one more method to obtain PLS values**
- ❑ **Good agreement was observed between AE event locations and DIC in pristine samples with holes, especially at cracking onset and initiation.**

Acknowledgements

(GE Aerospace, Evendale, Ohio)
- Roger Seither
- Dane Dale

(NASA GRC, Cleveland, Ohio)
- Dr. Jon C. Goldsby
- Dr. Joseph E. Grady [Retired]
- Dr. Elizabeth Young-dohe

(HX5, LLC, NASA GRC)
- Daniel Gorican
- Dr. Wayne D. Jennings
- Ralph J. Pawlik
- Ronald E. Phillips [Retired]