High-Temperature Mechanical Tensile Testing of Unidirectional SiC/SiC Composites using a Versatile Lamp Furnace

HT-CMC 11

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- Mechanical Testing Experimental Setup
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Introduction

- SiC/SiC ceramic matrix composites (CMCs) are candidates for high-temperature applications including new generation turbine engines due to:[1]
  - Reduced component weight and higher temperature capability when compared to superalloys
  - Improved energy efficiency and fuel consumption
  - Reduced NO_x and CO_2 emissions
- Further understanding of thermo-mechanical behavior of SiC/SiC CMCs is crucial for the continued implementation into advanced engines

Figure 1. CMC components in an advanced GE jet aircraft engine.[2]

[1] Brewer, D., "HSR/EPM Combustor Materials Development Program", Materials Science and Engineering A, Vol. 261, 284-291, 1999
2 J. Steibel, "Ceramic matrix composites taking flight at GE aviation," Am. Ceram. Soc. Bull, Vol 98 No. 3, 30-33.

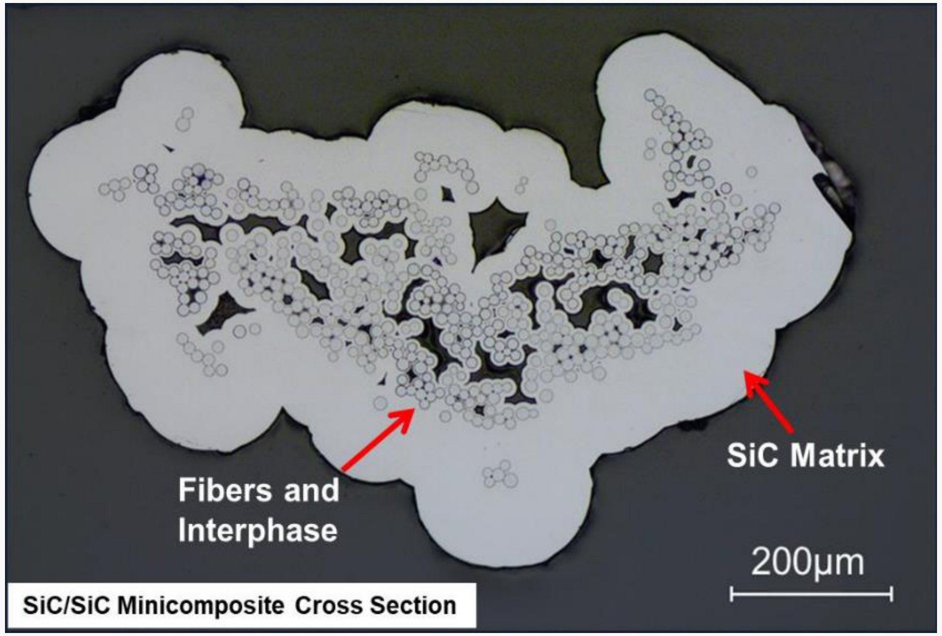
Objectives

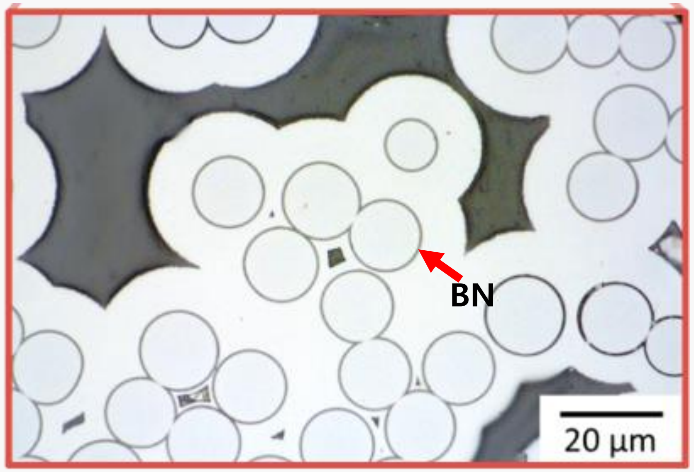
Conduct mechanical tensile testing of SiC/SiC minicomposites at elevated temperatures to gain insight into thermo-mechanical behavior

- Use multi-modal approach to monitor specimen damage progression in-situ
- Implement versatile lamp furnace for high temperature mechanical testing
- Compare two high temperature test setups: lamp furnace and conventional furnace
- Test and analyze temperature dependent mechanical behavior

SiC_f/SiC Minicomposite Samples

- Fundamental element of CVI SiC/SiC and Hybrid (CVI + PIP) SiC/SiC CMCs (macrocomposites)





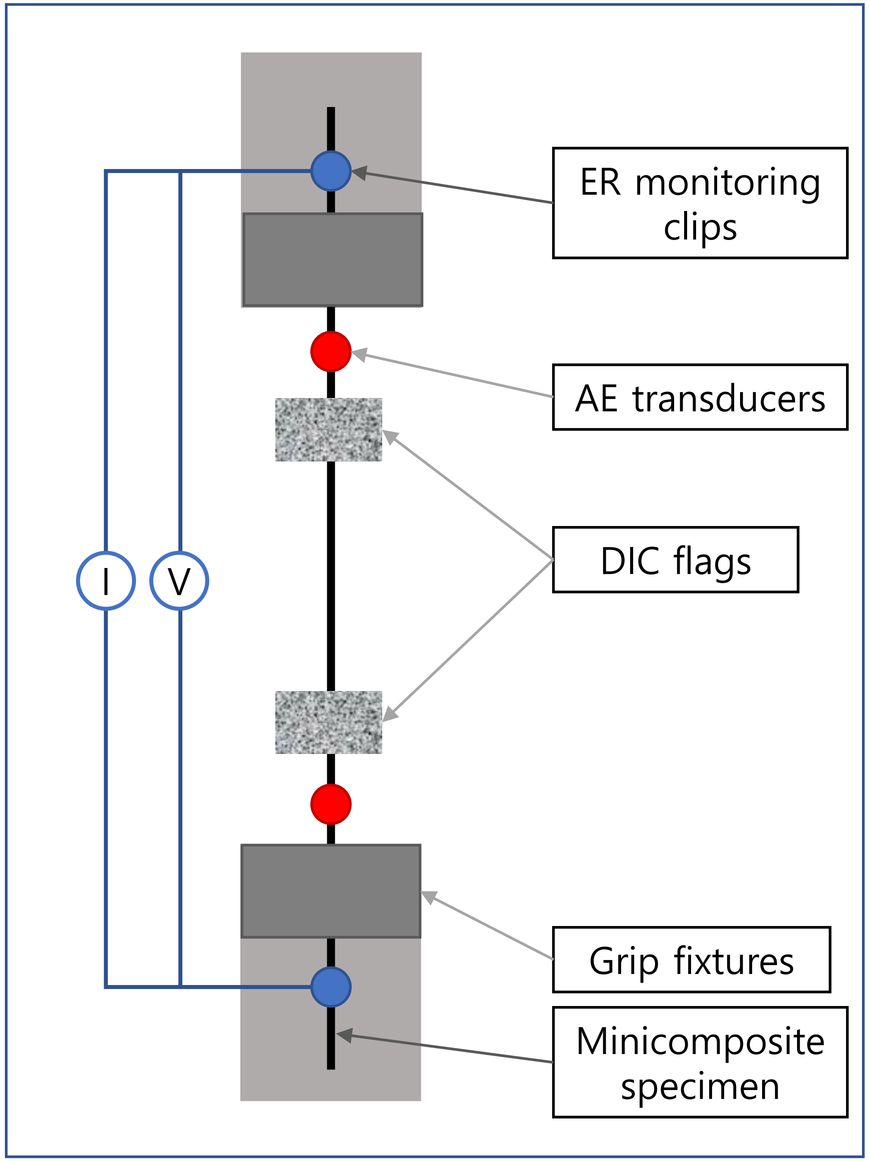
Images of cross-section of CVI SiC/SiC minicomposite

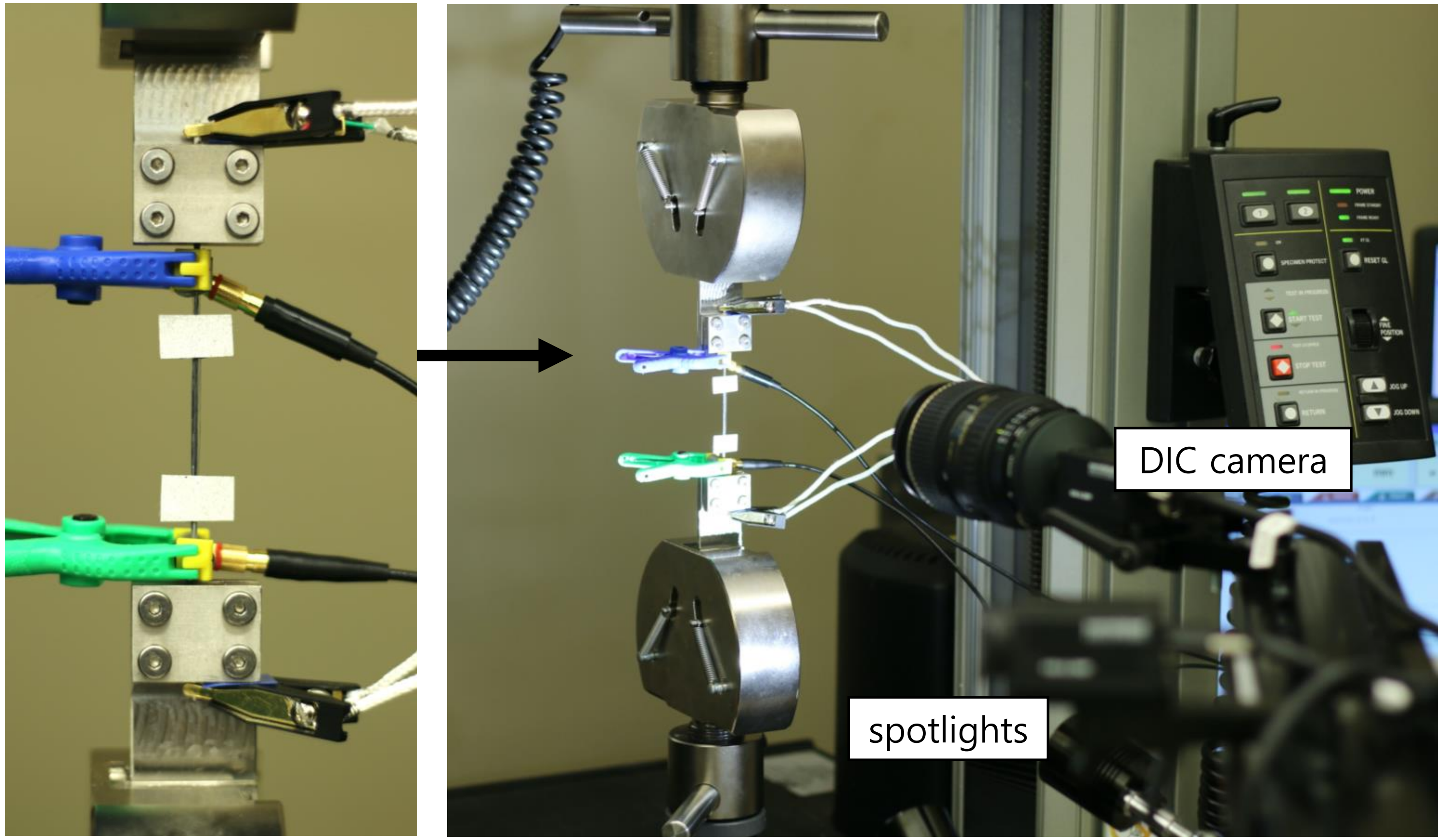
Sample	Hi-Nicalon S Content, %	CVI-SiC Matrix Content, %	BN Content, %	BN Thickness, μm	Cross Sectional Area (mm^2)
Batch 2	20.03	76.59	3.38	0.49	0.28

- Hi-Nicalon™ Type S fiber tow made by NGS (Japan)
- CVI BN interphase and CVI-SiC matrix deposited by Rolls-Royce (RR) HTC
- Same CVI SiC matrix as a CVI SiC/SiC macrocomposite

Tensile Testing and Characterization at Room Temperature

Mechanical Testing Experimental Setup

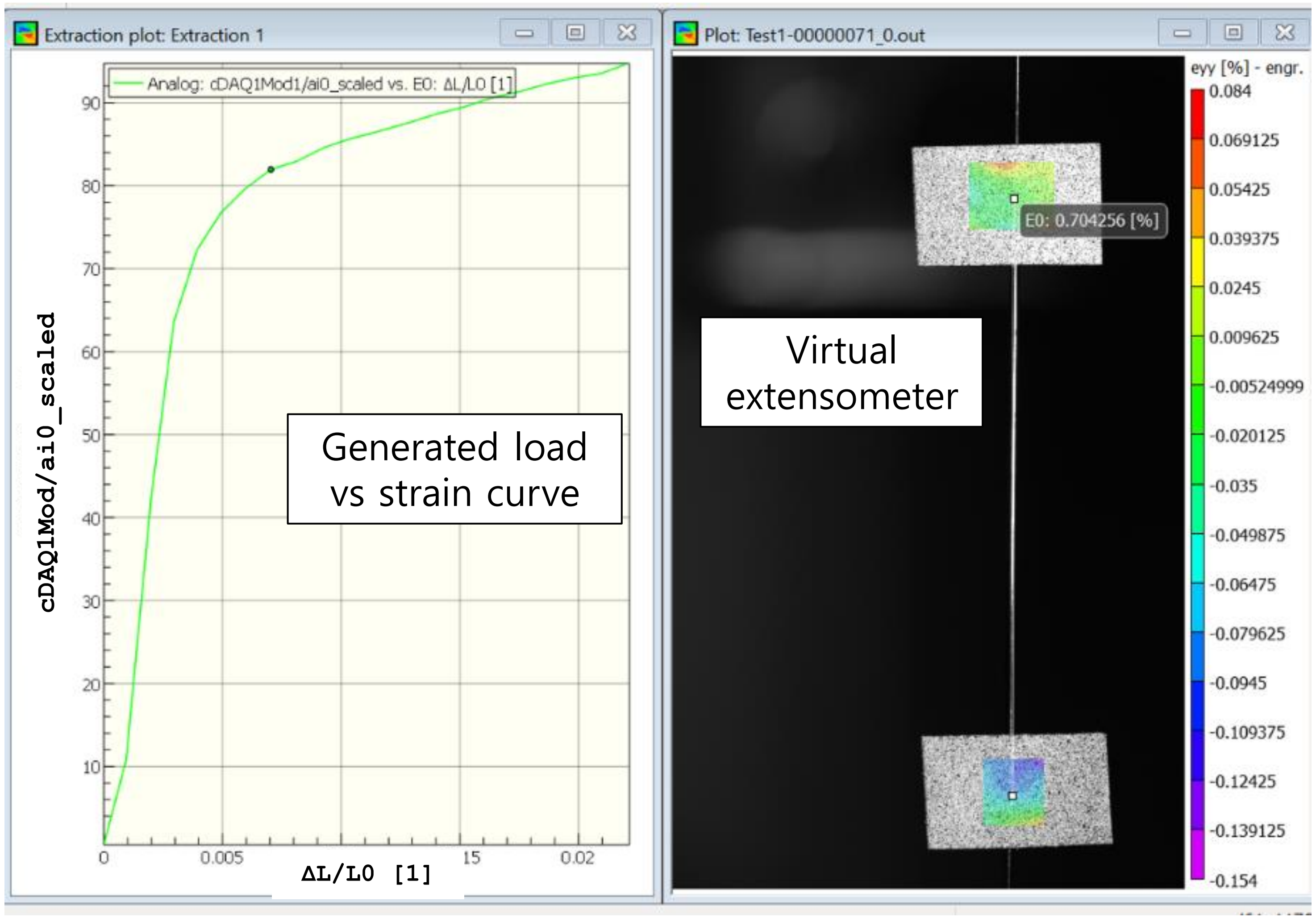




- Monotonic tensile testing of minicomposites
- 1 kN load cell and 0.127 mm/min crosshead displacement rate

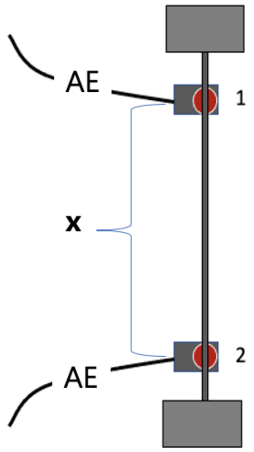
Digital Image Correlation (DIC)

- Utilizes successive imaging to gather surface information of a material undergoing deformation
- Often performed at room temperature using a speckle pattern
- Common uses:
  - Unidirectional elongation
  - Strain field mapping of specimen surface
  - Identification of progressing damage



Sample plot of strain data and virtual extensometer applied to captured image created in Correlated Solutions Vic-2D Software

Results: Digital Image Correlation & Acoustic Emission

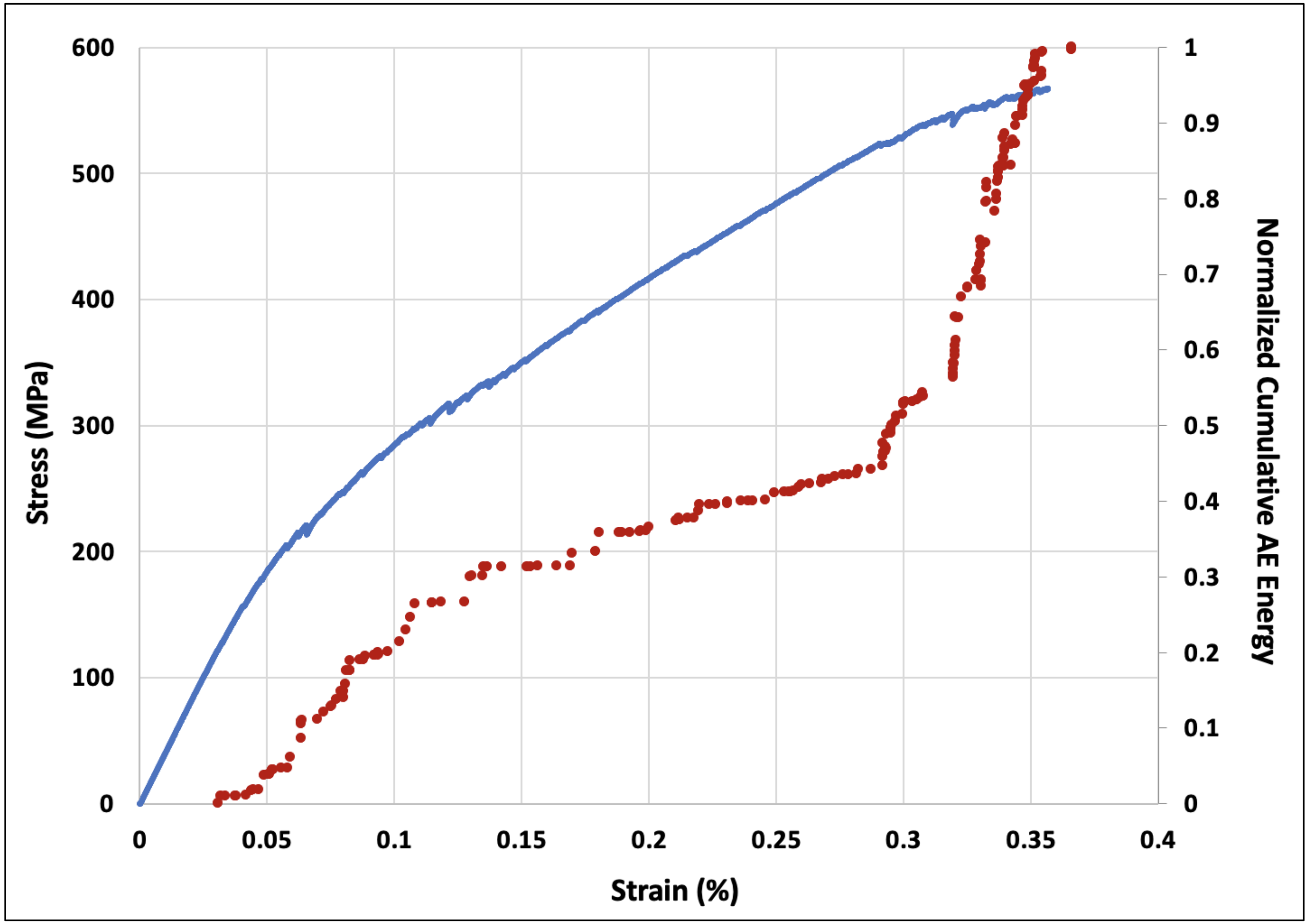


$$location = \frac{x}{2}\left(\frac{\Delta t}{\Delta t_x}\right)$$

x = distance between AE sensors

Δt = difference in event arrival times

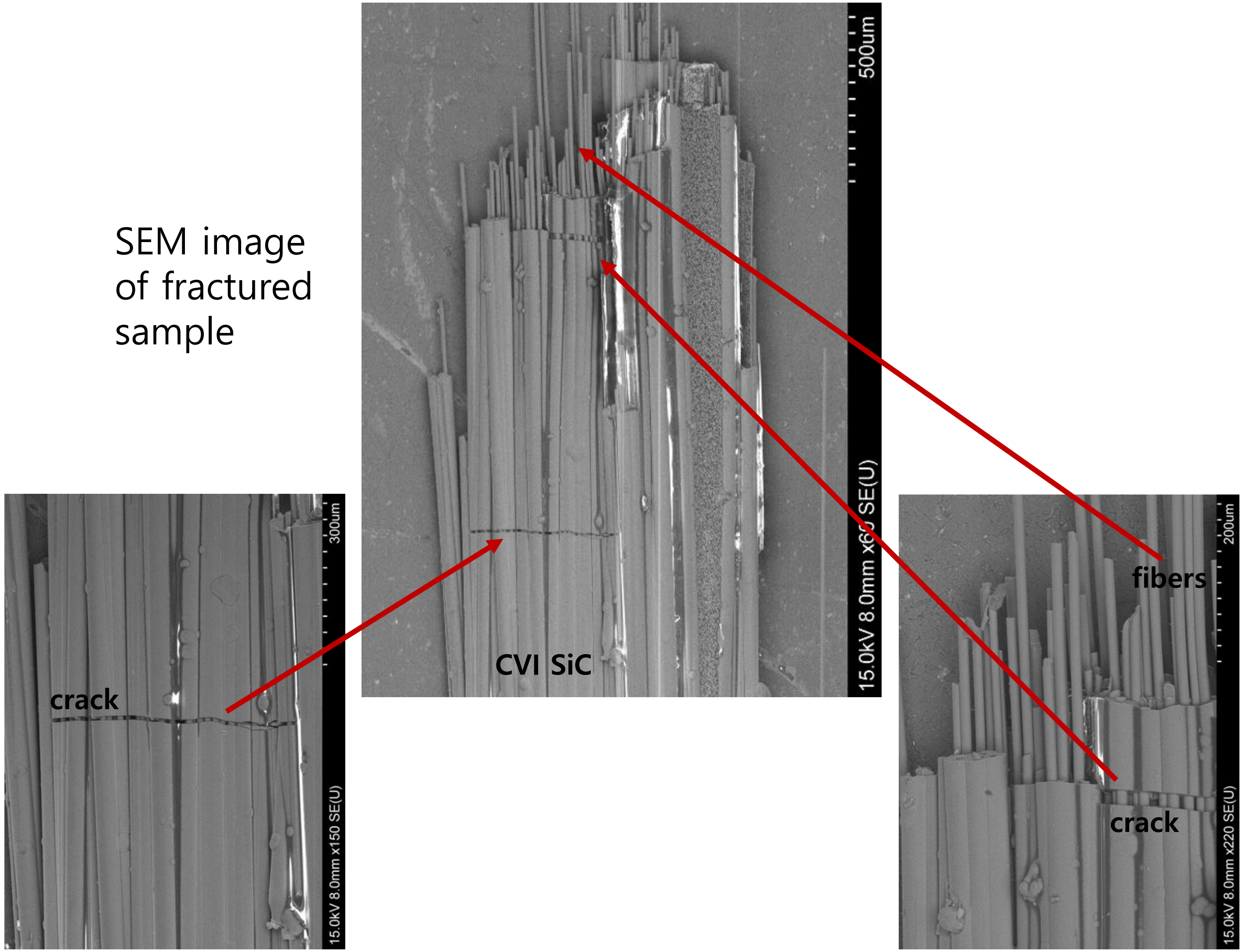
Δt_x = difference in arrival times across AE window

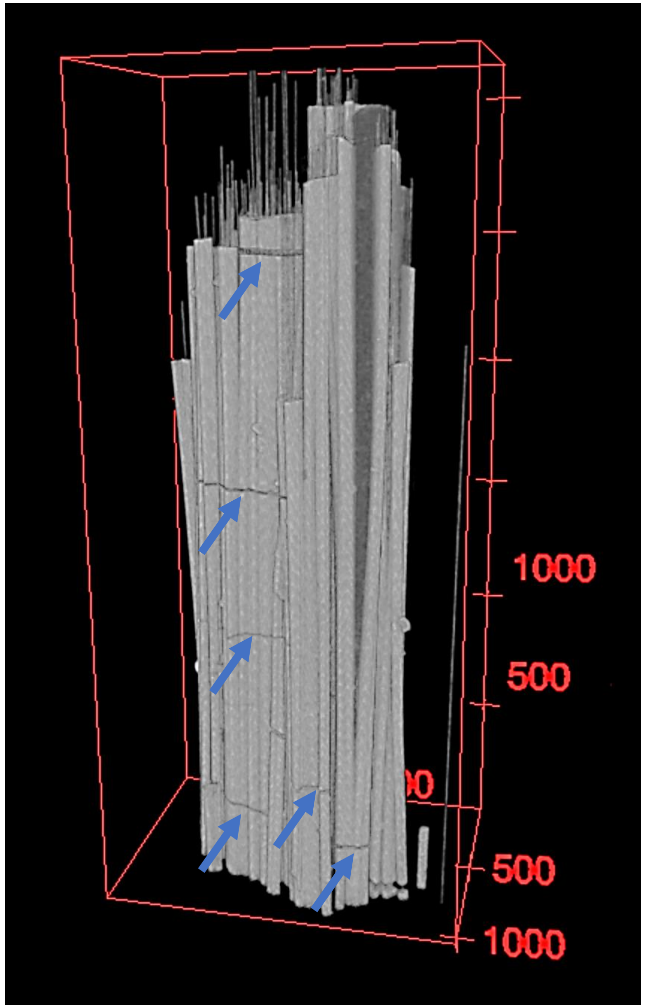


- DIC performed on minicomposite sample during room temperature fracture tests
- Plot of applied stress vs strain of minicomposite created using virtual extensometer

Results: Analyzing Specimen Cracking

SEM image of fractured sample



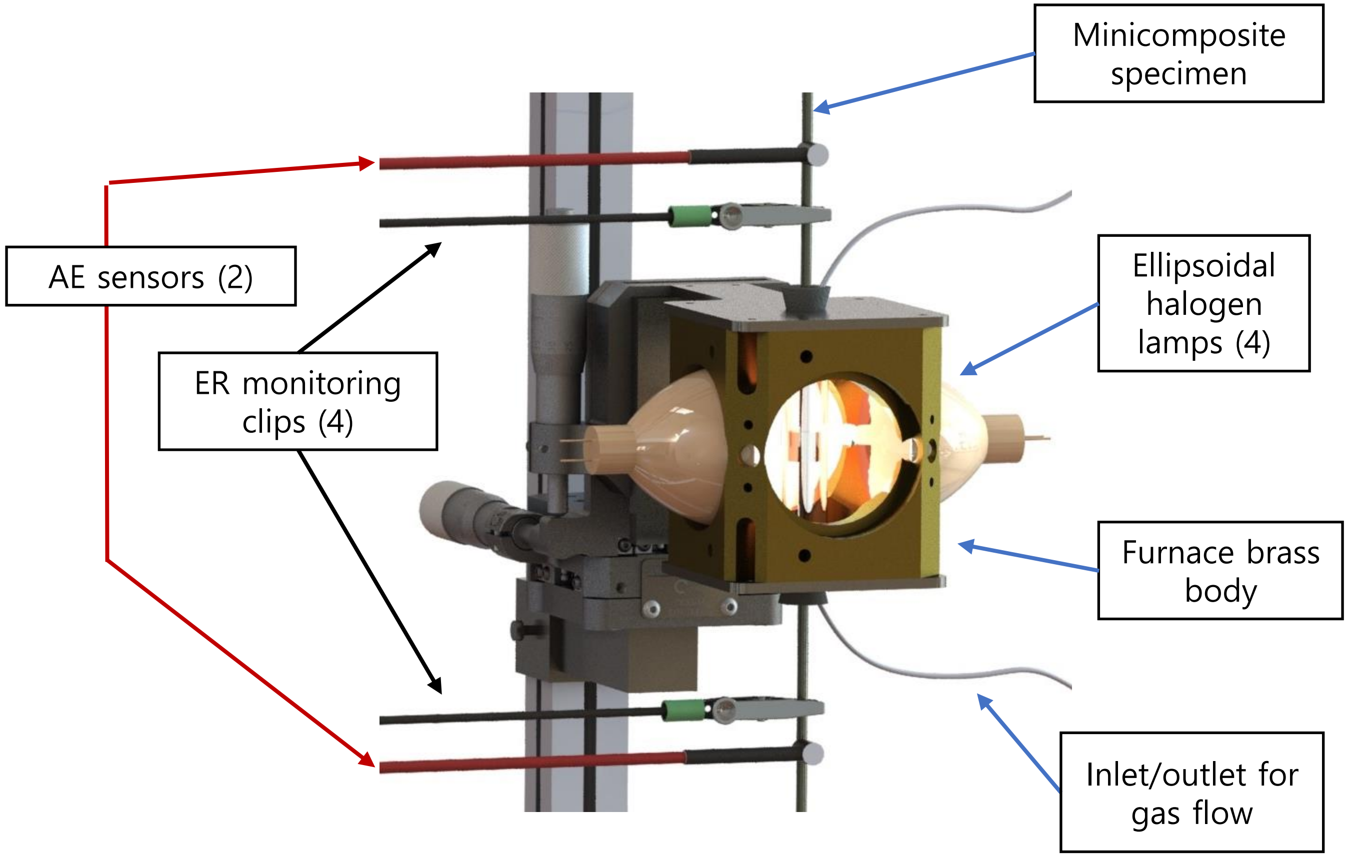


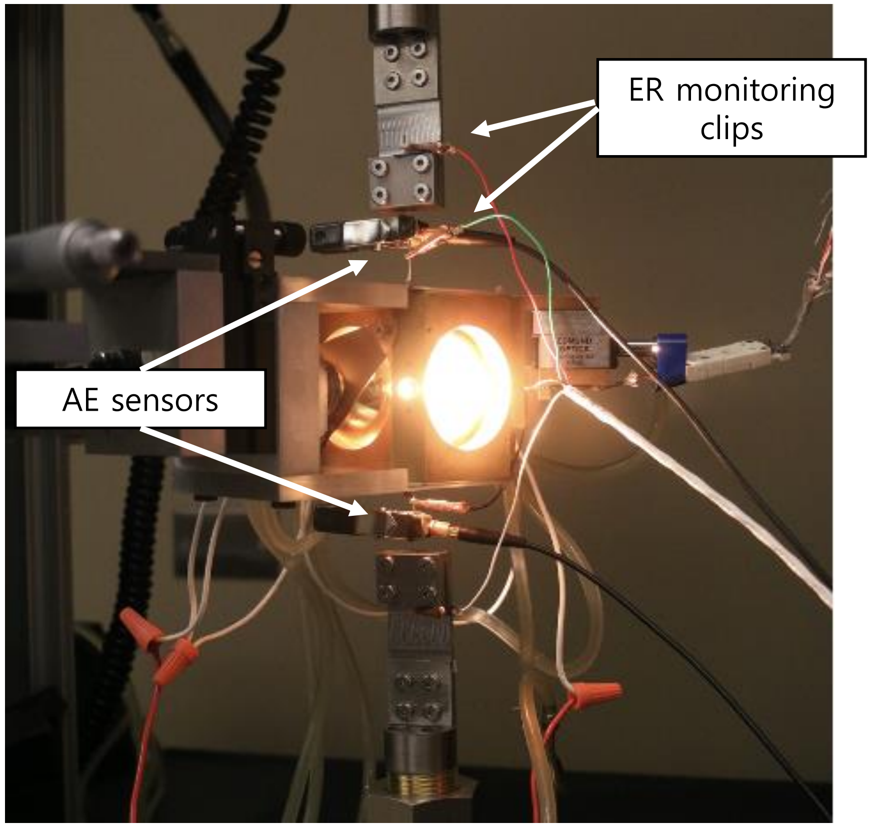
Micro-CT rendering of fractured minicomposite specimen

Specimen fracture surface showing cracks and fiber pullout, with fibers debonded from the SiC matrix.

Tensile Fast Fracture at High Temperatures

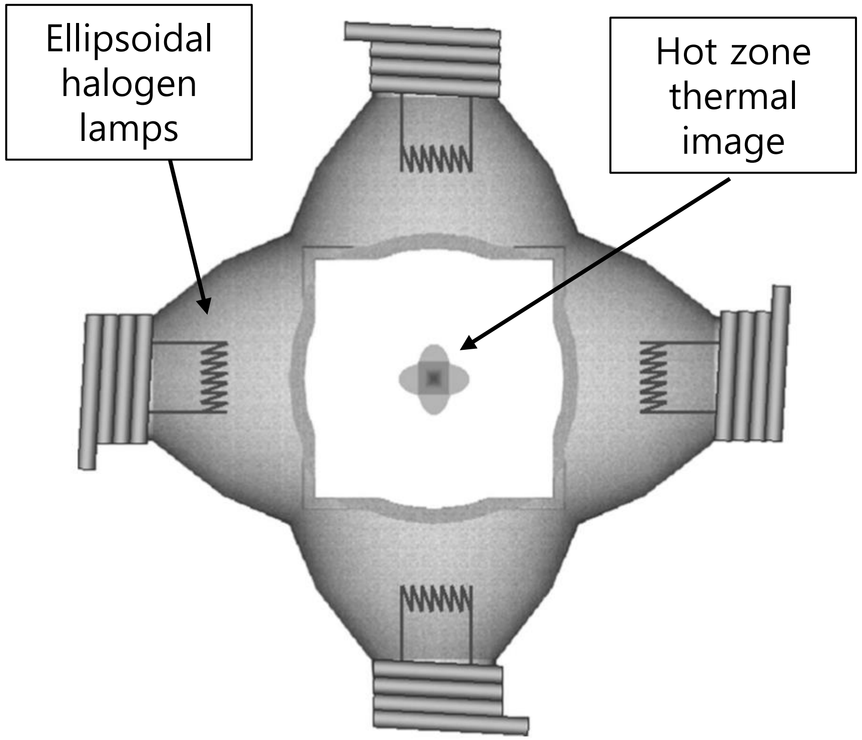
High Temperature Experimental Setup – Lamp Furnace





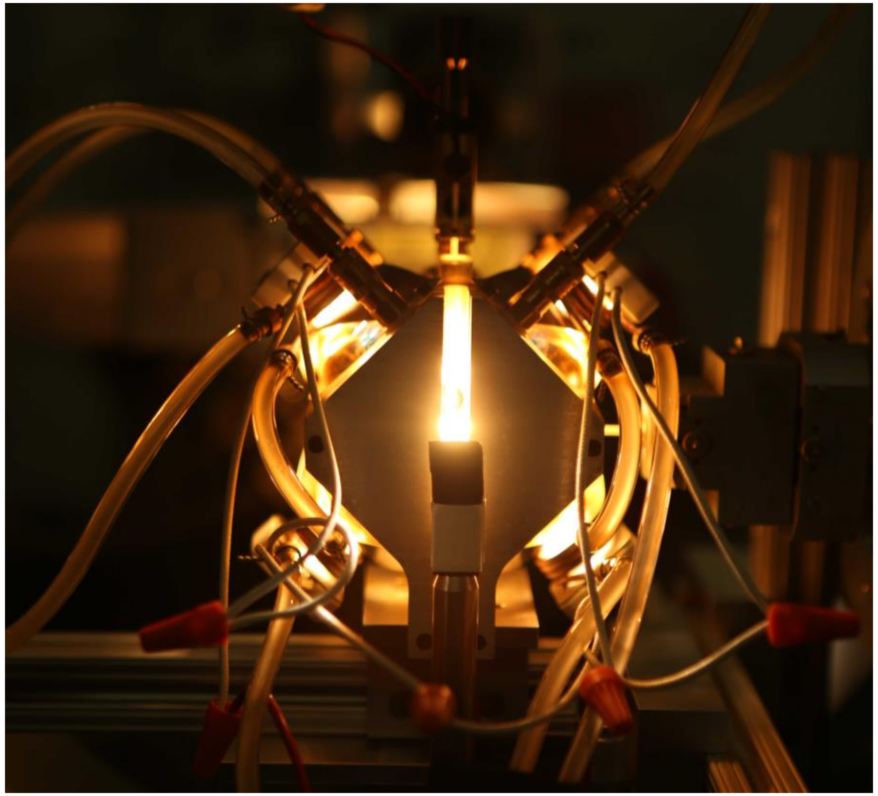
Quadrupole Lamp Furnace (QLF)

- Versatile thermal image furnace
- Uses four halogen lamps with ellipsoidal reflectors
- Hot zone of ~4 mm
- Samples can be heated up to 2000°C in air, 1700°C in inert atmospheres



Schematic of thermal profile generated from ellipsoidal reflectors[1]

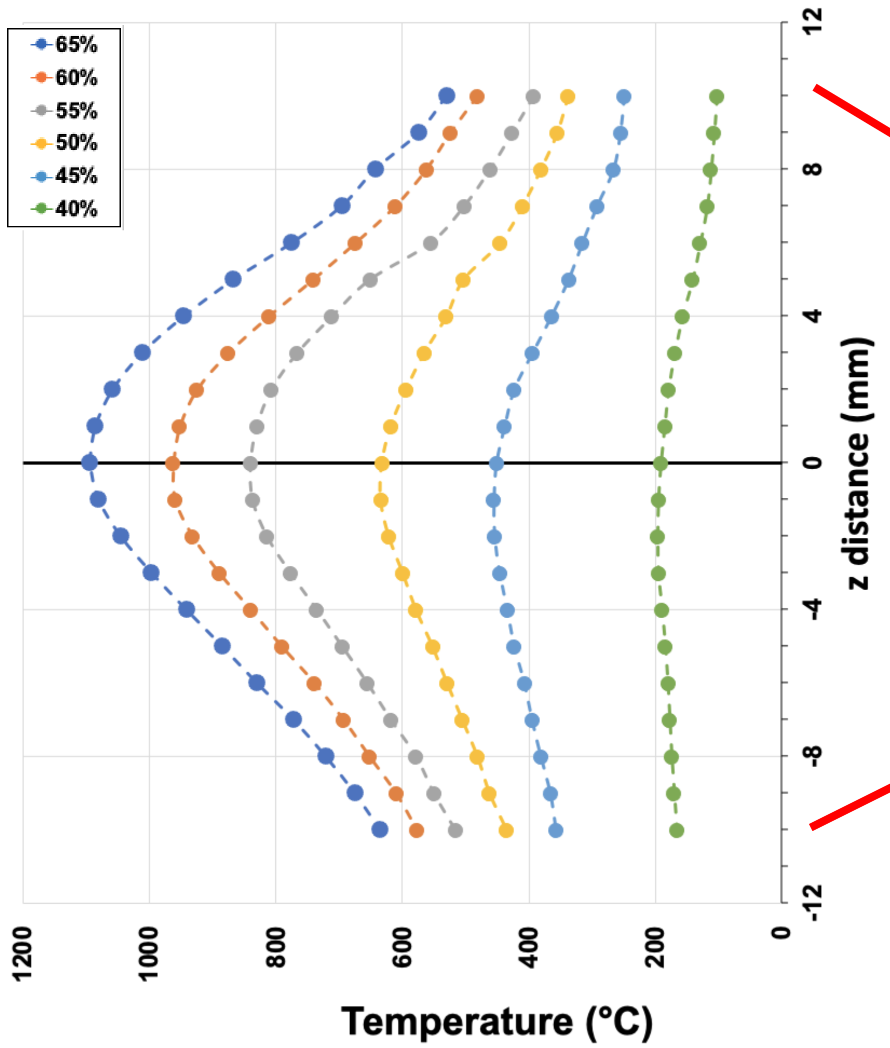
top view



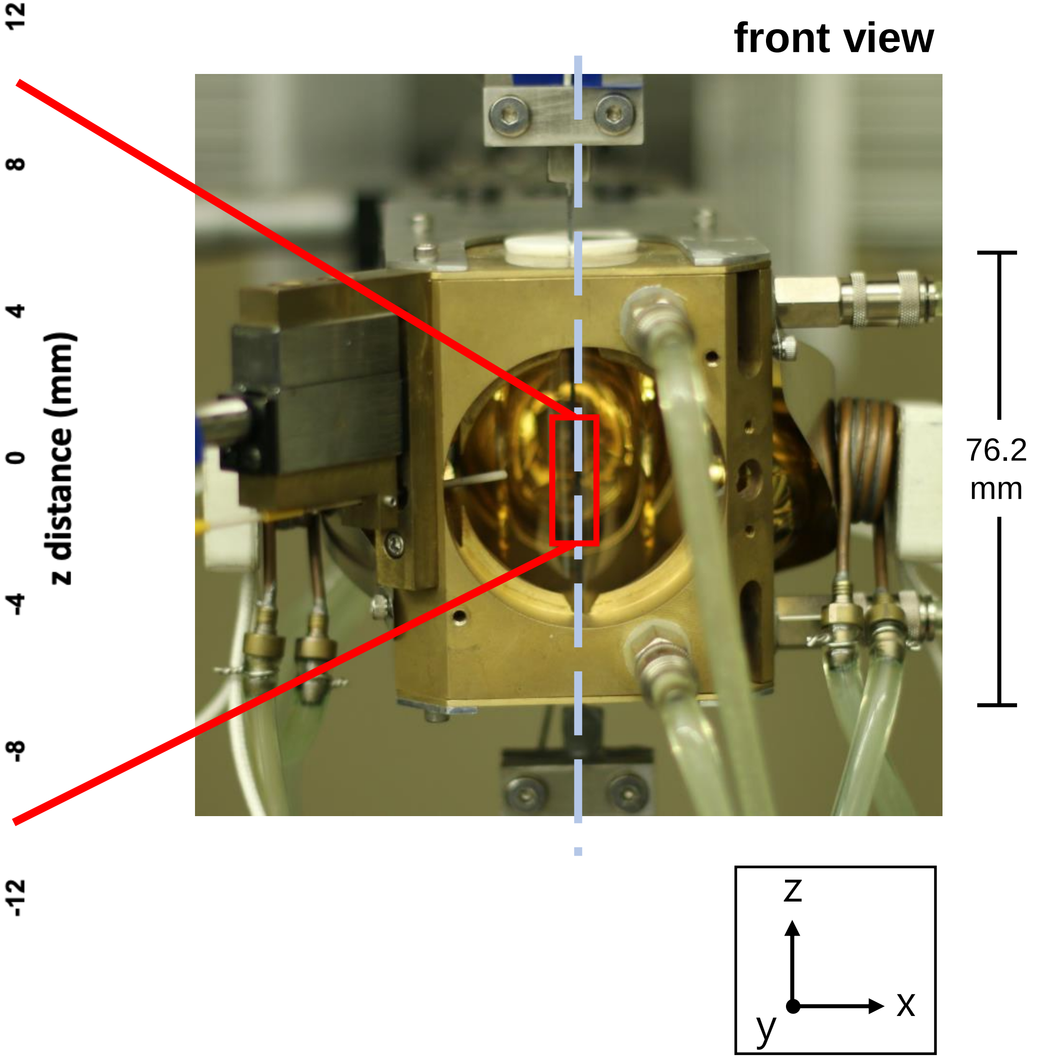
QLF in operation at the XPD beamline at the National Synchrotron Light Source (NSLS II) at Brookhaven National Laboratory[2]

[1] Sarin, P., et al., "Quadrupole lamp furnace for high temperature (up to 2050K) synchrotron powder x-ray diffraction studies in air in reflection geometry", Review of Scientific Instruments, Vol. 77, 2006.
[2] Sarin, P., Lowry, D., and Ghose, S., "Lamp furnace for in-situ diffraction and total scattering studies in controlled atmospheres." Poster.

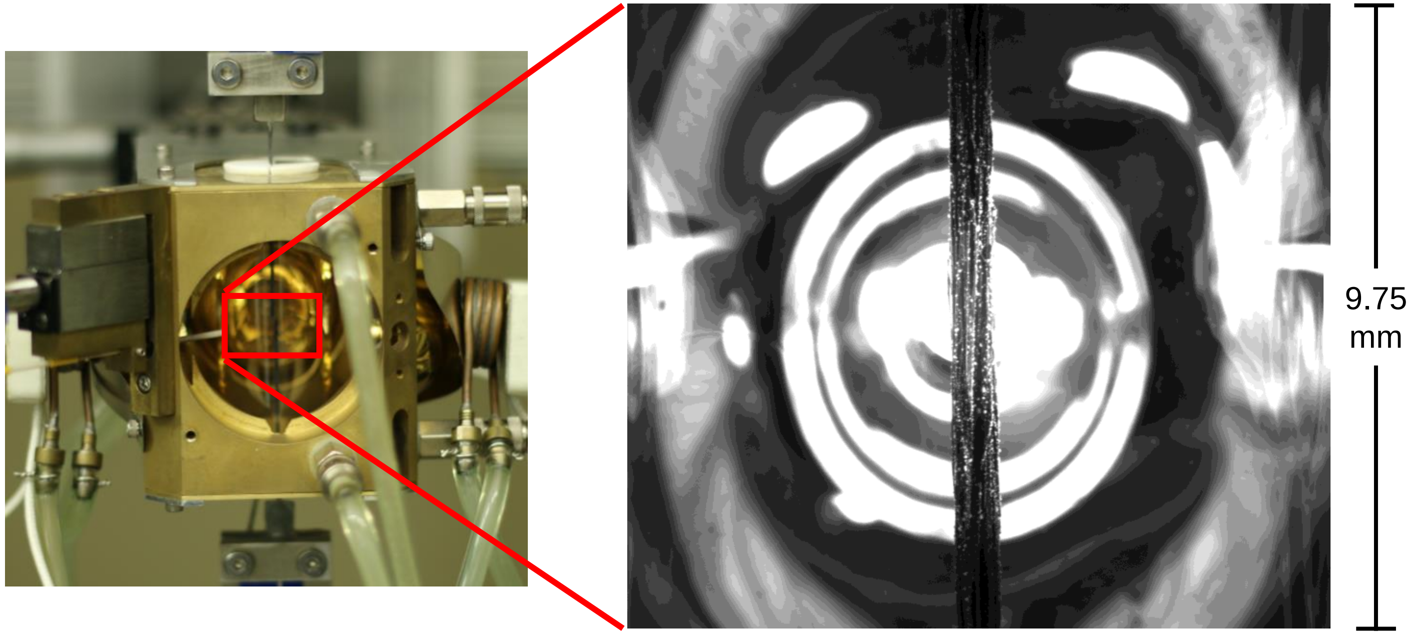
QLF Thermal Profile



Effect of power and distance from the center on temperature distribution along the z-axis

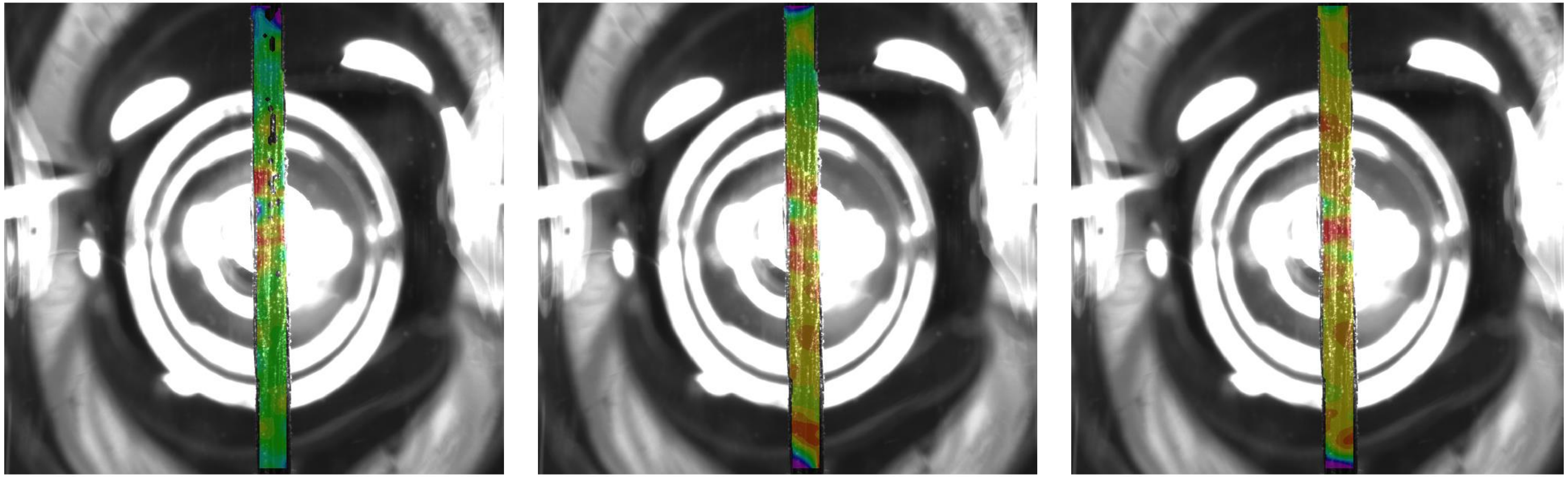


High Temperature DIC



- Sample mounted longitudinally through furnace center while subjected to tensile loading
- Furnace geometry allows for line-of-sight view to the specimen and hot zone center
- High temperature DIC technique: observe change in specimen strain based on thermal profile created

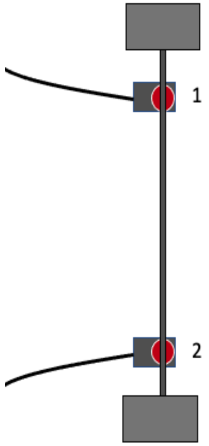
Results: High Temperature DIC

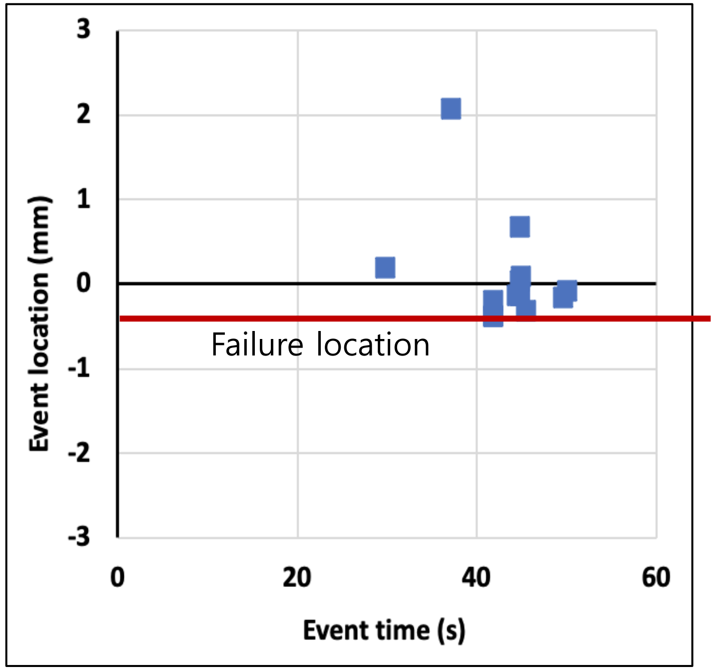


20 MPa | 50 MPa | 135 MPa

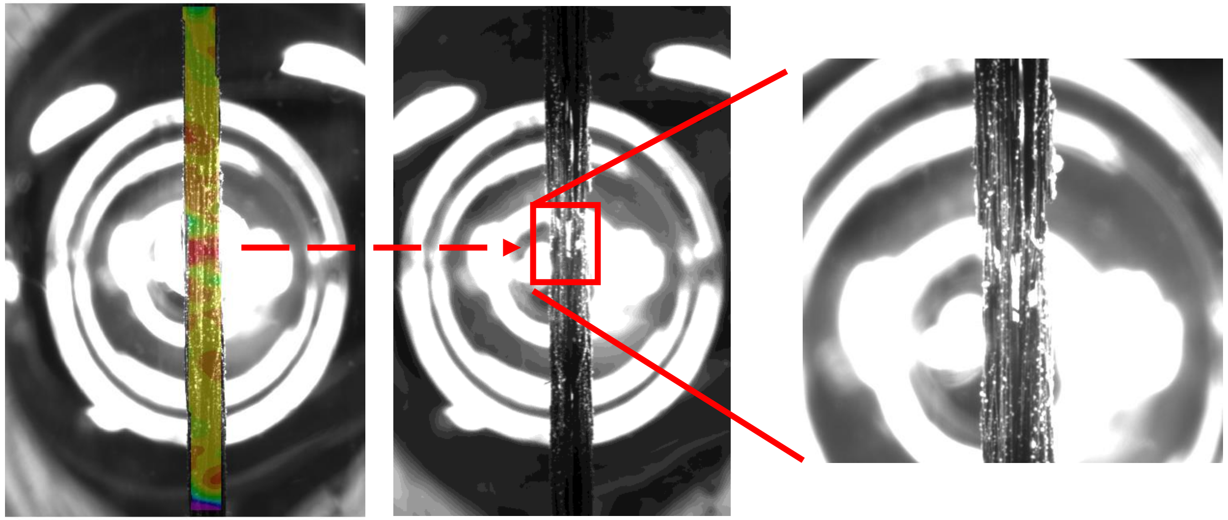
- Surface mapping of strain in y direction as load is increased throughout fast fracture test
- Specimen subjected to tensile loading at 1200°C at 0.127 mm/min displacement rate
- Failure at 149 MPa
- Concentrated regions of increased strain near furnace hot zone

Results: Acoustic Emission & DIC





Global AE activity mapped along sample gage as a function of event time

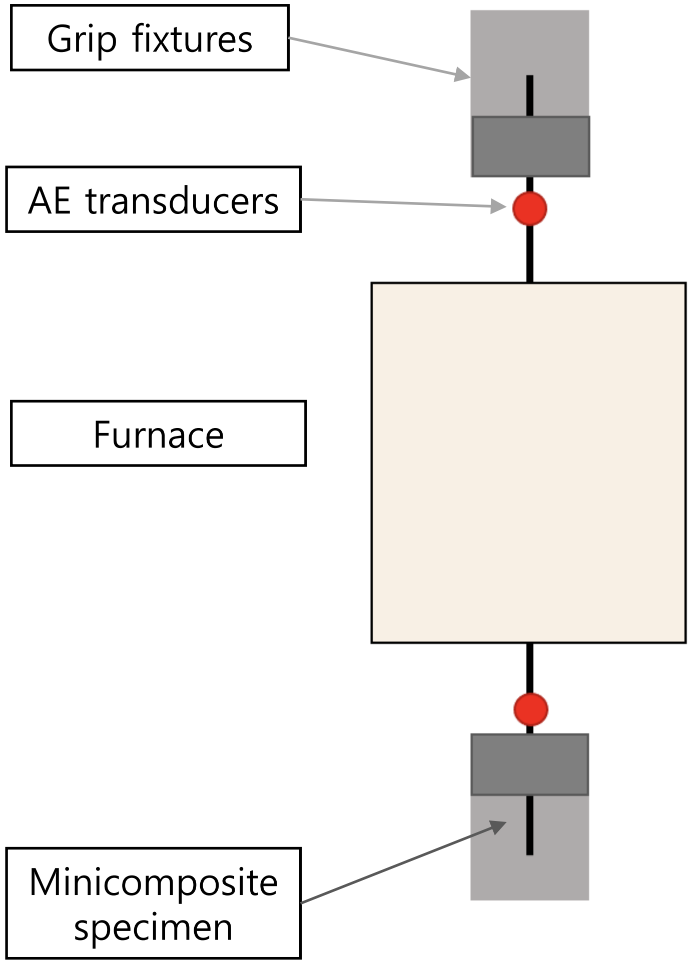


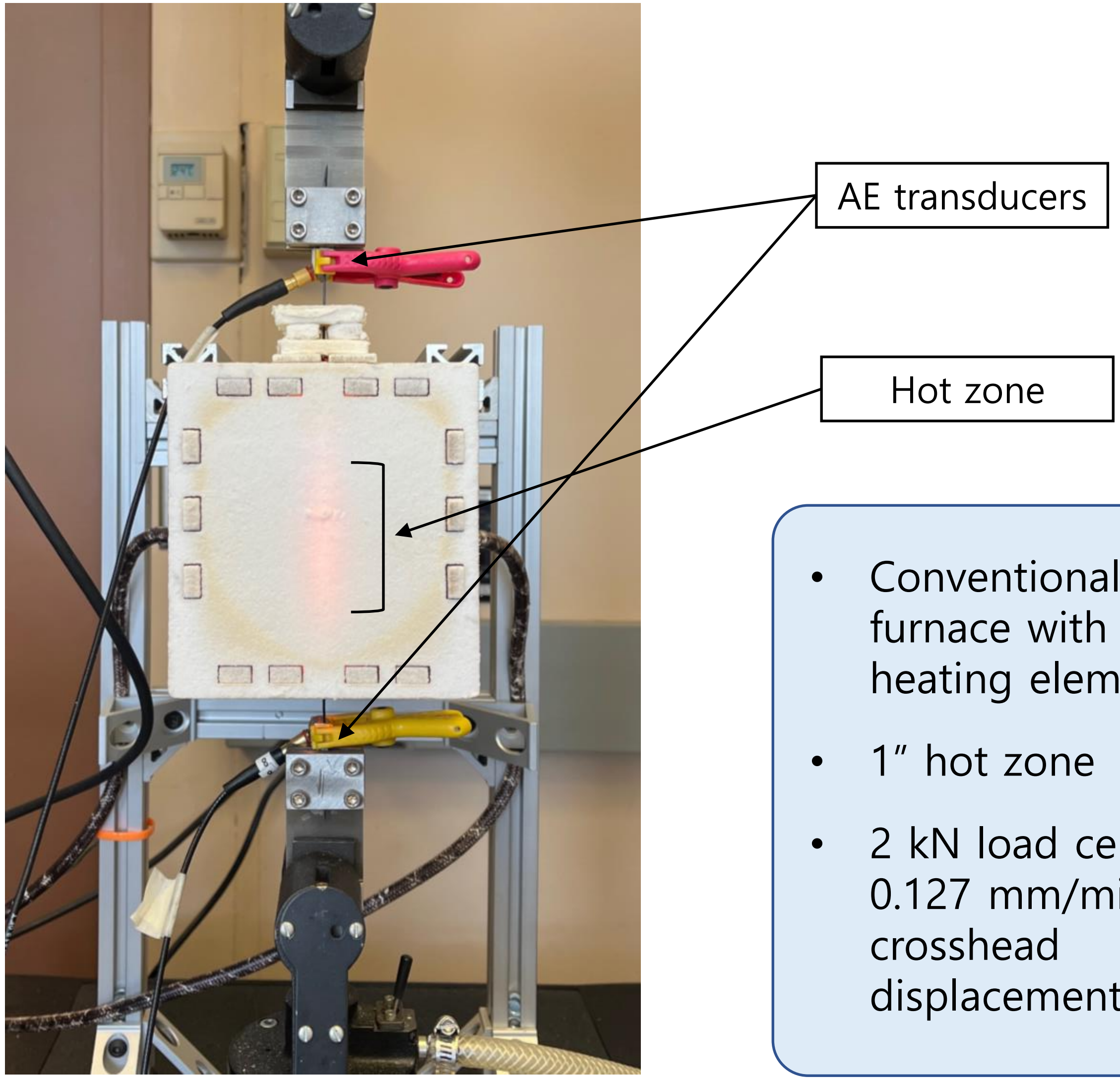
135 MPa

Failure

- Regions of concentrated strain correspond to specimen ultimate failure location
- AE events are localized towards increased DIC strain region and hot zone

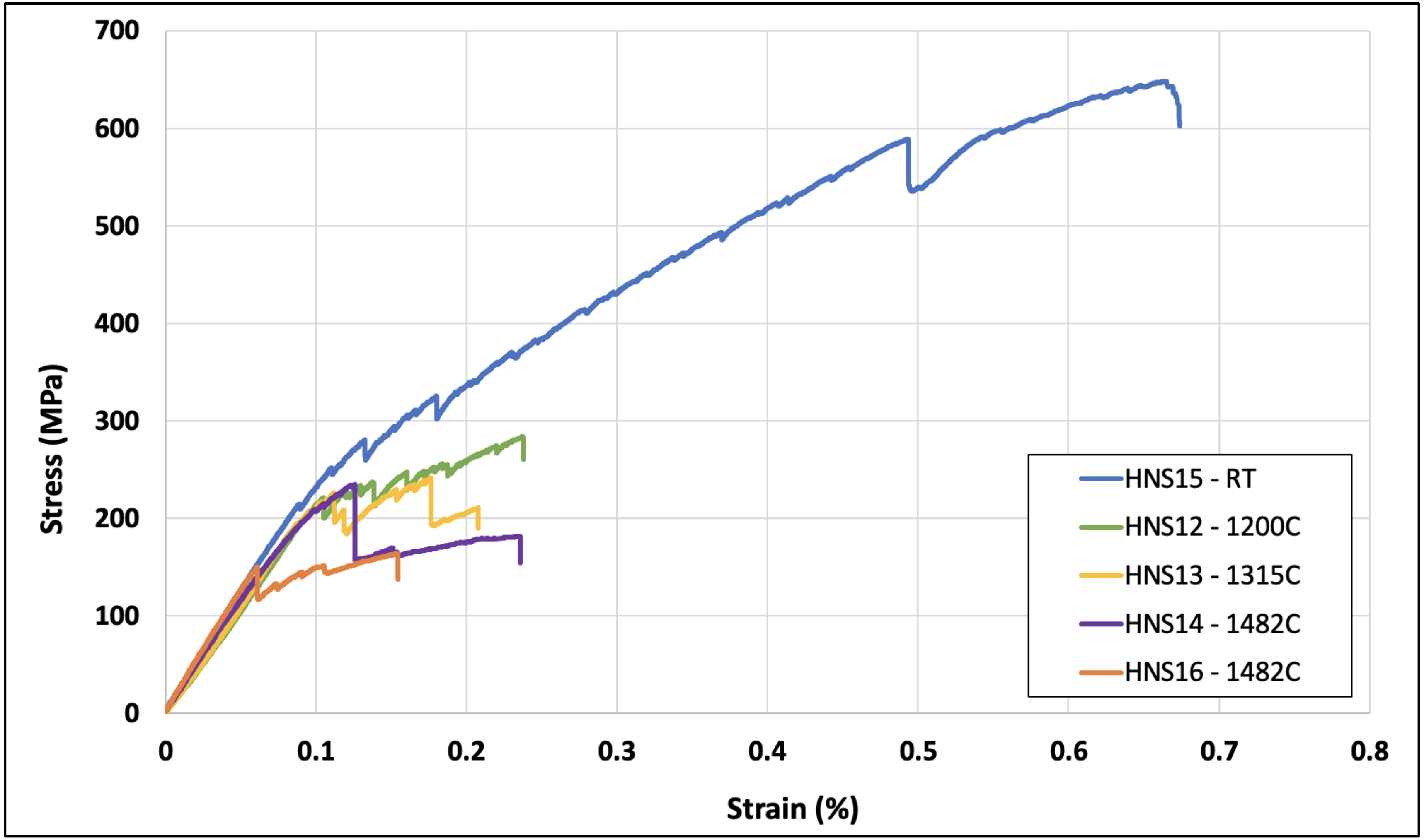
High Temperature Experimental Setup – Conventional Furnace





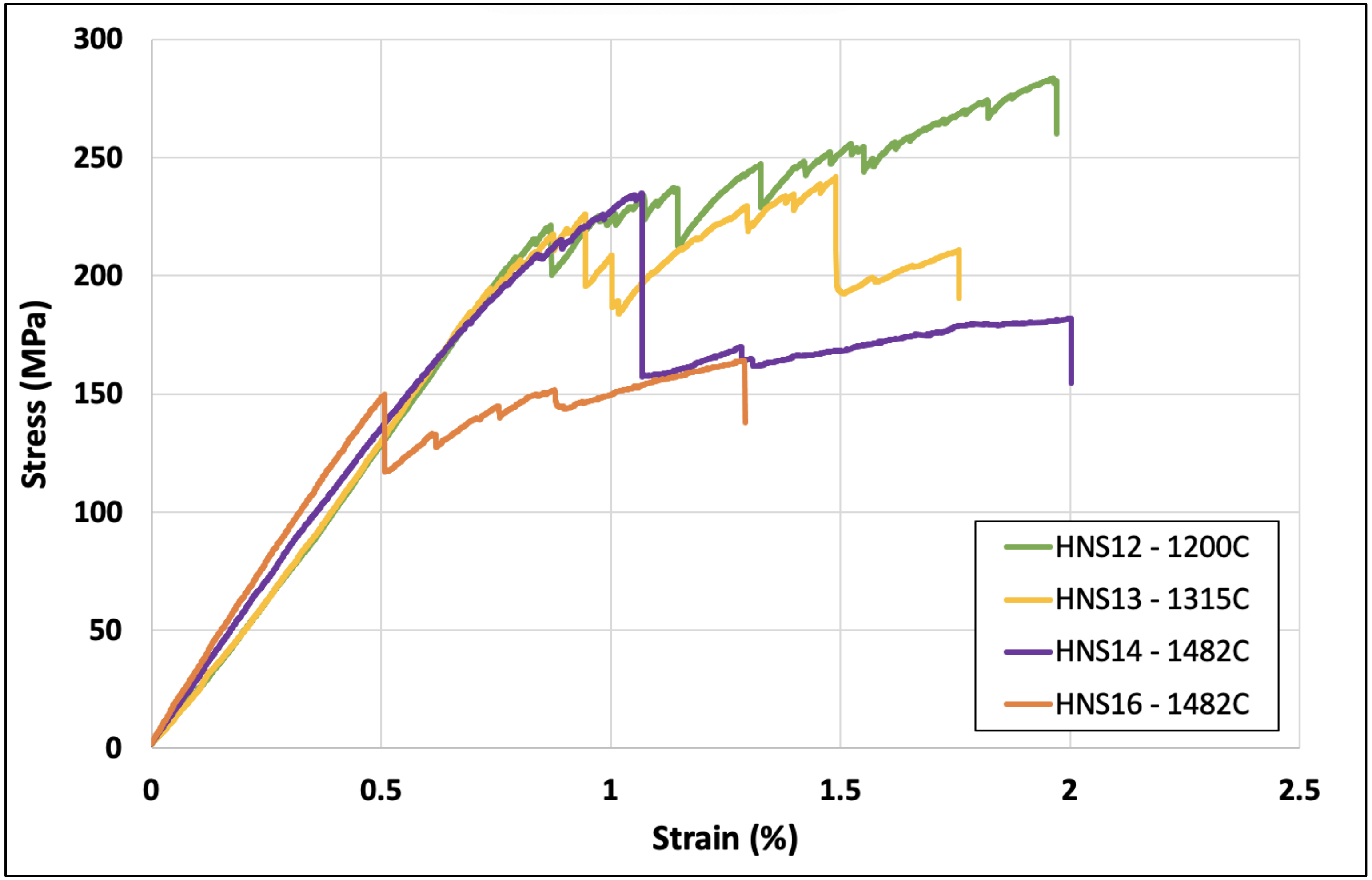
- Conventional slit furnace with $MoSi_2$ heating element
- 1″ hot zone
- 2 kN load cell with 0.127 mm/min crosshead displacement rate

Results: Temperature Dependent Mechanical Behavior



- Minicomposite stress as a function of strain for tests conducted at room temperature, 1200°C, 1315°C, and 1482°C
- Ultimate tensile strength and toughness decrease as test temperature is increased
- Matrix cracking strength decreases at higher testing temperatures

Results: Temperature Dependent Mechanical Behavior

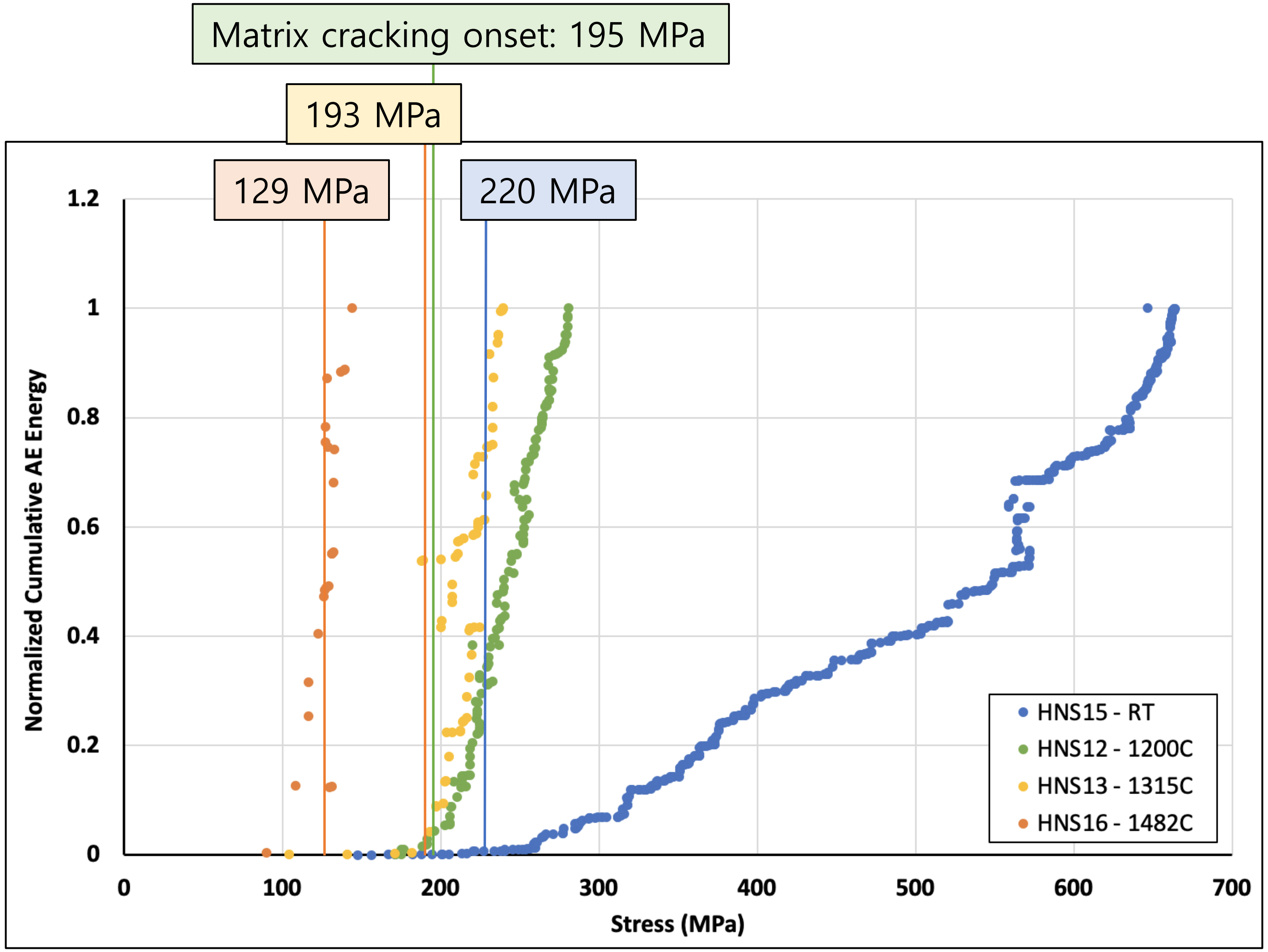


- Minicomposite stress as a function of strain for high temperature tests
- Strain calculated across hot zone length of 1″
- Toughness decreases as testing temperature is increased

Results: Temperature Dependent AE Energy

- Normalized cumulative AE energy vs minicomposite stress
- Onset of matrix cracking characterized by first loud AE event
- Onset of matrix cracking decreases as testing temperature increases
- Less number of AE events recorded at higher test temperatures

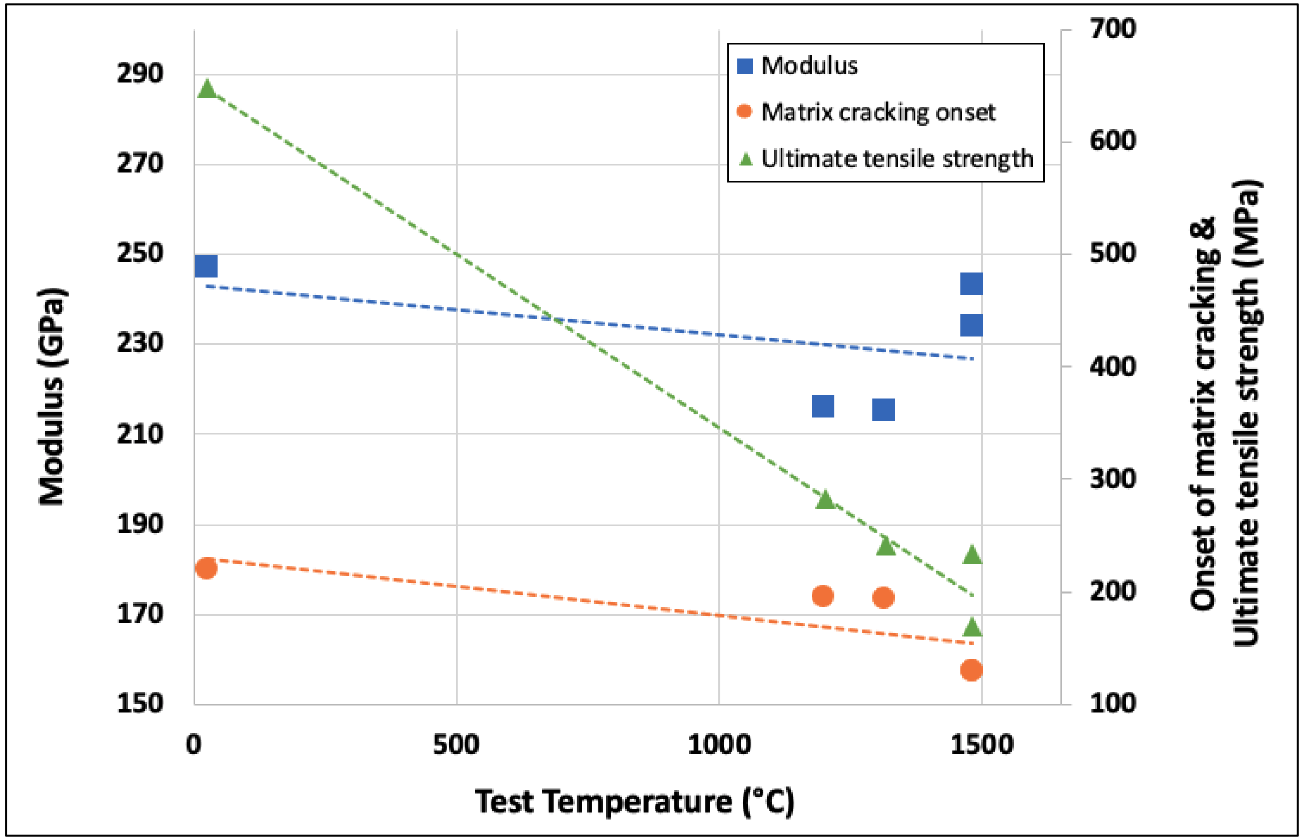
Sample ID	HNS15	HNS12	HNS13	HNS16
Temperature	25°C	1200°C	1315°C	1482°C
# of AE events	557	138	86	42



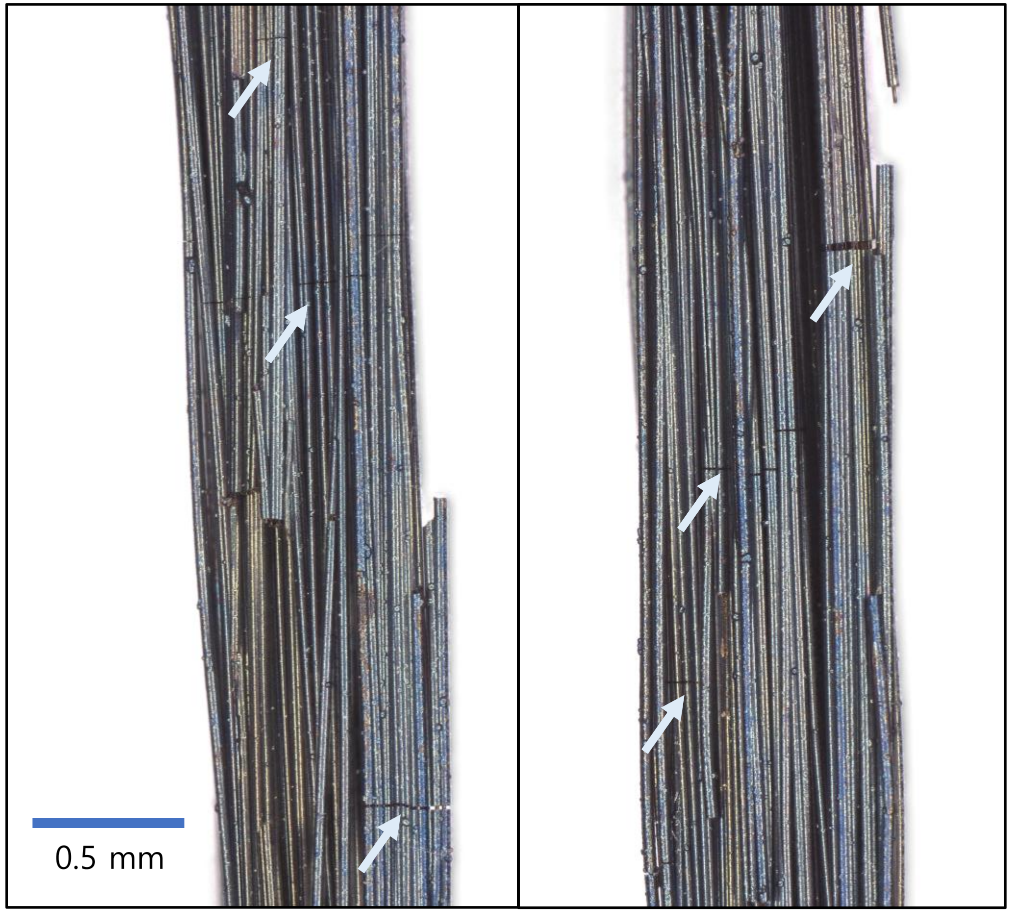
Results: Specimen Moduli, UTS, and Matrix Cracking Onset

Sample ID	Testing Temperature	Modulus (GPa)	Ultimate tensile strength (MPa)	Onset of matrix cracking (MPa)
HNS15	25°C	247 GPa	648 MPa	220 MPa
HNS12	1200°C	216 GPa	283 MPa	195 MPa
HNS13	1315°C	215 GPa	241 MPa	193 MPa
HNS14	1482°C	225 GPa	234 MPa	---
HNS16	1482°C	243 GPa	169 MPa	129 MPa

- Modulus of specimen tested at room temperature is higher than that of 1200°C, 1315°C, and 1482°C tests
- Ultimate tensile strength and onset of matrix cracking values continue to decrease as test temperature increases



Results: Analyzing Specimen Cracking



- Optical images of specimen tested at 1482^{o}C
- Specimen fracture surface showing cracks and fiber pullout, with fibers debonded from the SiC matrix
- Plan to further analyze cracks along specimen gage length and calculate crack density

Summary

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- Fracture testing of SiC/SiC minicomposite specimens in ambient and elevated temperatures is being performed
- Multiple damage monitoring techniques were implemented in-situ (AE, ER, DIC)
- Furnace constructed for high temperature minicomposites testing
- Thermal profile measurements of lamp furnace completed
- Two high temperature testing setups compared: lamp furnace and conventional furnace
- Temperature dependence of specimen elastic moduli, ultimate tensile strength, and onset of matrix cracking observed:
  - Moduli of specimens tested at room temperature are higher than for specimens tested at high temperatures
  - Specimen toughness, UTS, and matrix cracking onset values continue to decrease as test temperature increases
- Samples characterized after testing (SEM, μCT, optical microscopy)

Acknowledgements

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- Mr. Achyuth T. Guthai
- Mr. Kyle Messer

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