SiC/SiC Lifetime Limiting Mechanisms

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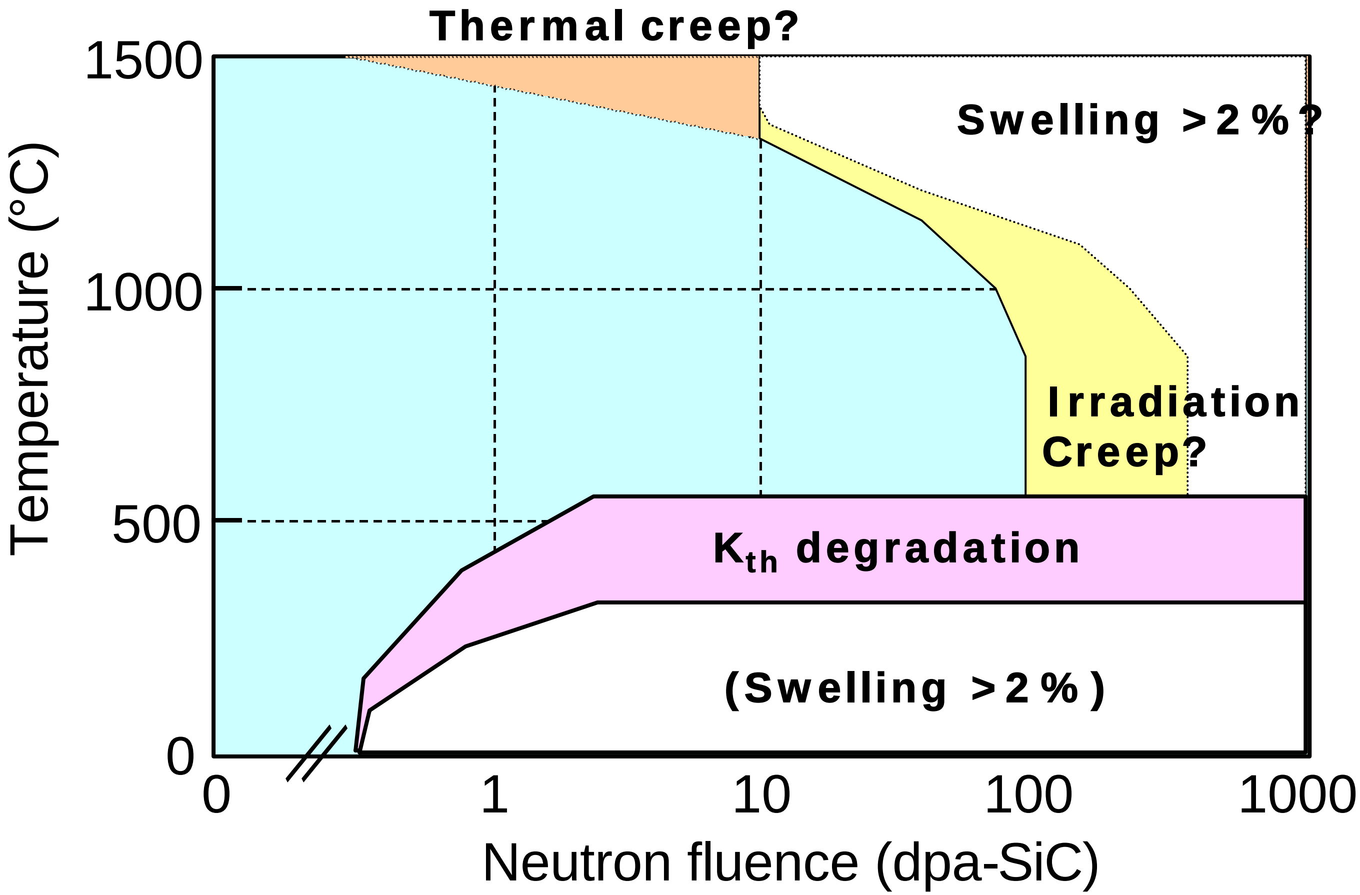
Very Preliminary 'Design Window' – Do Not Refer!



- Issues have not yet well identified. Potential issues not indicated include: He-effect on strength and fracture toughness, fatigue, oxidation at very low P_{O_2} and P_{H_2O}, microstructural and microchemical instability @high-T.
- Irradiation database is definitely lacking. Data on older generation materials are not applicable.

Potential Lifetime Limiting Issues

- ‘Cold’ issues:
  - Fatigue
  - Thermal creep
  - Environmental degradation

- Neutron-related issues
  - Swelling
  - Irradiation creep
  - Strength/toughness degradation due to irradiation
  -
  -

Fatigue Lifetime

- The fatigue limit at room temperature and inert environment is much higher than the proportional limit, while that in an oxidation environment coincides with the proportional limit.
- Fatigue behavior depends on fiber architecture. The matrix cracking initiates typically on the large inter-bundle pores at a crossover point of 0/90 fiber bundles in plain-weave composites.

Zhu, et al.
Composites Sci. Tech.
59 (1999) 833-851.

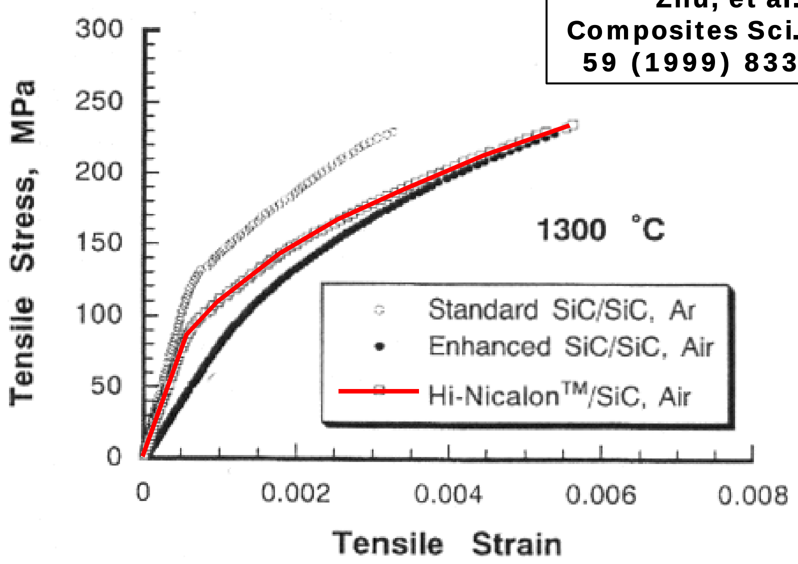


Fig. 4. Tensile stress versus strain in Hi-Nicalon™/SiC in air, enhanced SiC/SiC in air and standard SiC/SiC composites in argon at 1300°C.

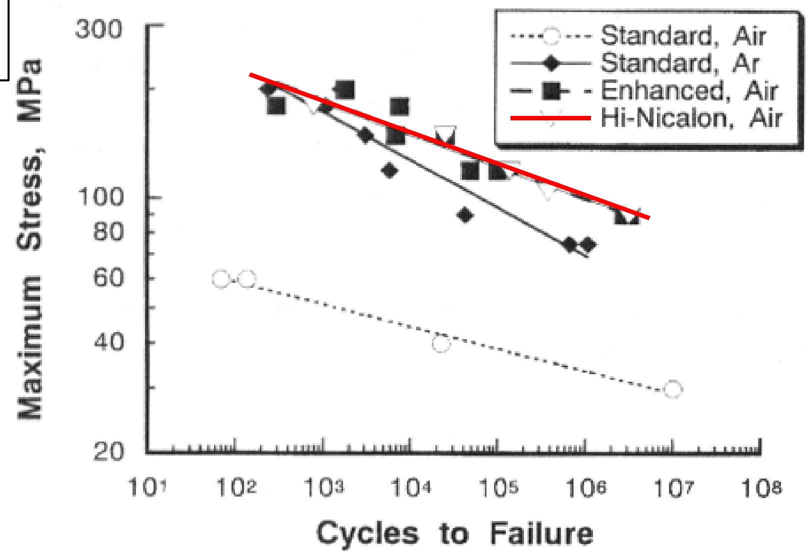


Fig. 9. Maximum stress versus cycles to failure of Hi-Nicalon™/SiC in air, enhanced SiC/SiC in air, and standard SiC/SiC in air and argon at 1300°C.

Fatigue Models for Composites

- Linear strength degradation theory (Broutman and Sahu):

$$s_{res} = s_U - (s_U - s_{\max}) \cdot \frac{N}{N_f}$$

$$\mathrm{N_f} = \text{fatigue life at } s = s_{\max}$$

- Non-linear residual strength degradation theory (Yang and Liu):

$$s_{res}^{\;c} = s_U^{\;c} - s_0^{\;c} \cdot K \cdot (s_{\max} - s_{\min})^d \cdot N$$

$$\mathrm{c} = \text{damage development parameter}$$

$$K, d = \text{S-N parameters where } K \cdot (s_{\max} - s_{\min})^d \cdot N_f = 1$$

- Global strain theory (O'Brien)

  Combines residual strength degradation and modulus degradation

- Residual stiffness theory (Liu and Lessard)

$$\frac{E}{E_0} = 1 - KN^{2/(2+b)} s_{\max}^{\;2b/(2+b)} \left(1 - \frac{s_{\max}}{s_U}\right)$$

$$\mathrm{K, b} = \text{constants}$$

➤ Applicability of the existing models needs to be studied.

On the Existing Data on Fatigue

- Existing fatigue data are mostly on Nicalon-CG and Hi-Nicalon composites. Large elastic modulus mismatch in those composites does not exist in advanced fiber composites.
- 'Commercial grade argon' environment in which most fatigue tests at around 1000°C have been carried out provides 'passive oxidation' condition for SiC, where silica glass coating decelerates crack propagation and interphase erosion.
- Cracking behavior largely depends on reinforcement architecture. Data on unidirectional and 2D composites may not be relevant to 3D composites.
- Wearing behavior of the F-M interface may substantially be influenced by the initial surface roughness of the fibers. Highly heat-resistant fibers are high temperature-treated and therefore have enhanced surface roughness.

Fatigue-induced Cracking in Plain-Weave SiC/SiC

High stress   Low stress

Zhu, et al.
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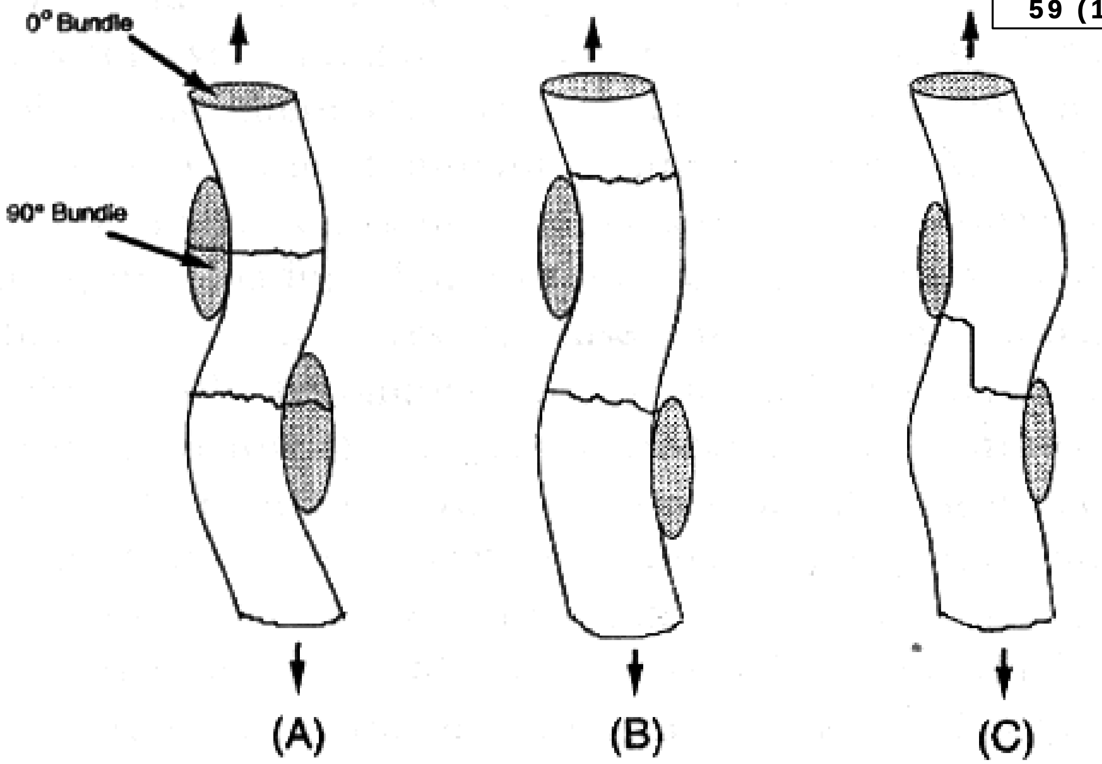


Fig. 7. Schematic diagram of fracture modes of 0° bundles.

- Inter-bundle pores and fiber waviness are affecting the low stress fatigue fracture of plain-weave composites.

Fatigue-induced F-M Interface Wearing

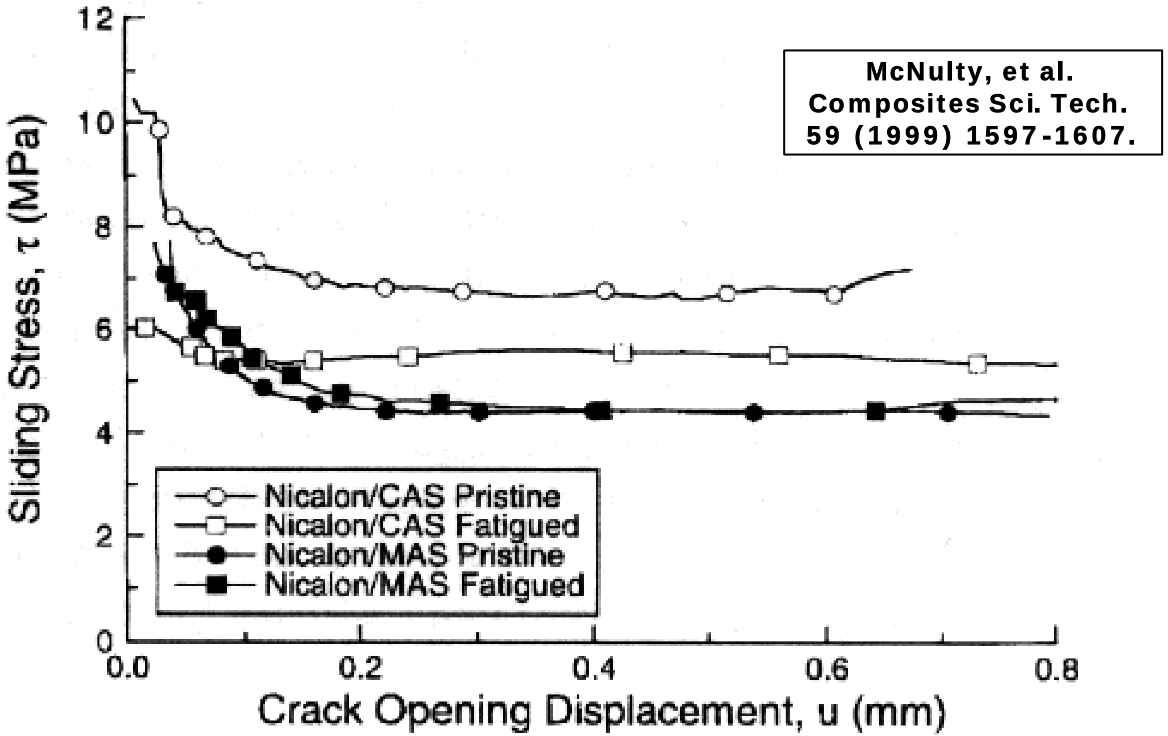
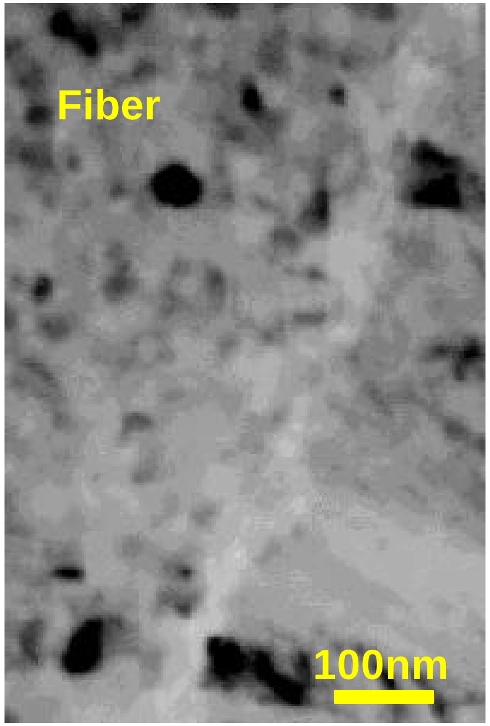


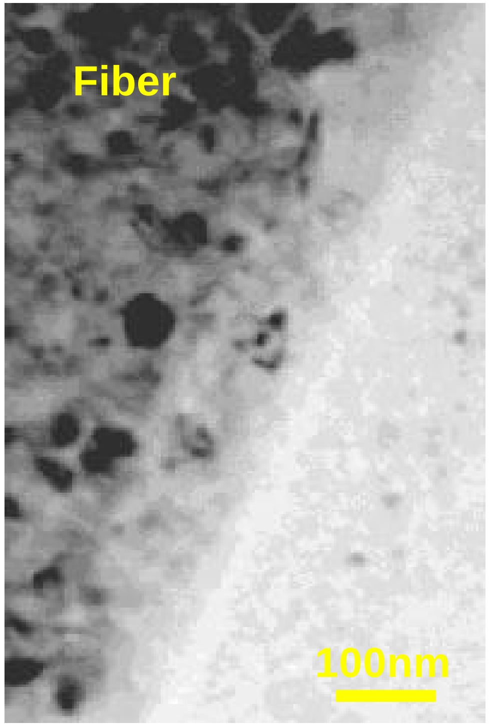
Fig. 12. Results of fiber pull-out experiments. For clarity, only the data for the fatigued materials are shown in (a) and (b).

Surface Roughness of Advanced SiC Fibers

Hi-Nicalon



Hi-Nicalon Type-S



Tyranno-SA(1997)

Thermal Creep of NL/CVI-SiC

Zhu, et al.
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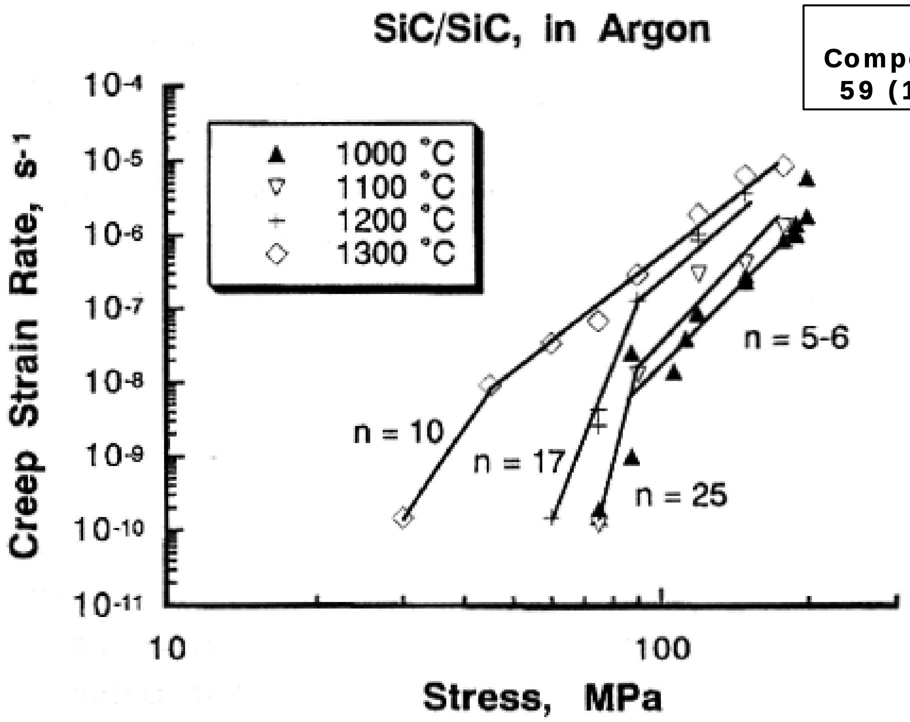

Fig. 13. Tensile minimum creep strain rate versus stress in argon at 1000, 1100, 1200 and 1300°C.

- Creep deformation of CVI-SiC matrix is controlling the creep rate of Nicalon-CG-reinforced composites.
- Advanced fibers may alter the creep mechanism.
- Reduced matrix porosity will improve the apparent creep rates.

Creep Rate – Rupture Time Correlation

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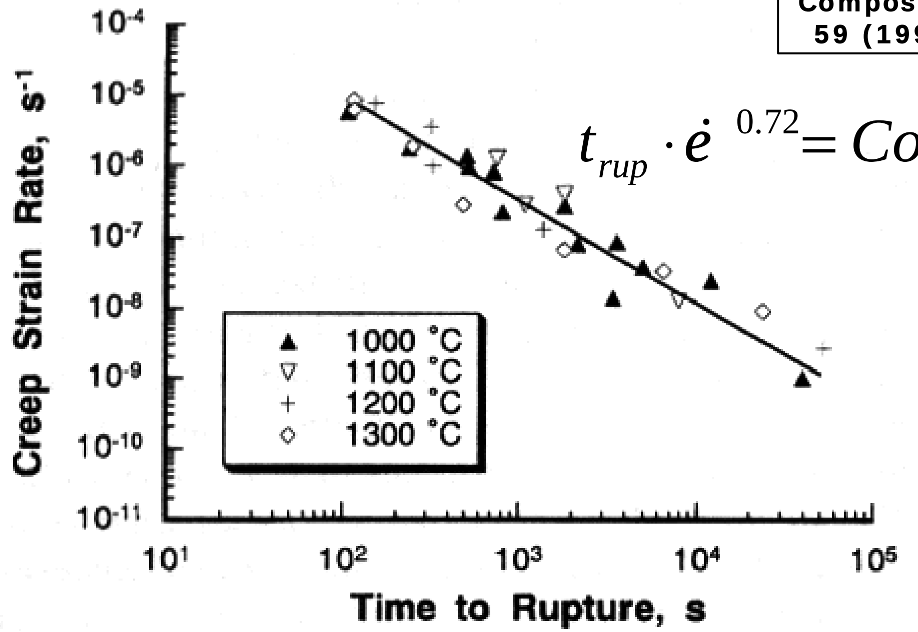


$$t_{rup} \cdot \dot{e}^{\,0.72} = Const.$$

Fig. 16. Tensile minimum creep strain rate versus time to rupture at different stresses in argon at 1000, 1100, 1200 and 1300°C.

- The steady-state creep strain rate versus time to rupture falls into the Monkman-Grant relationship.

A Larson-Miller Plot

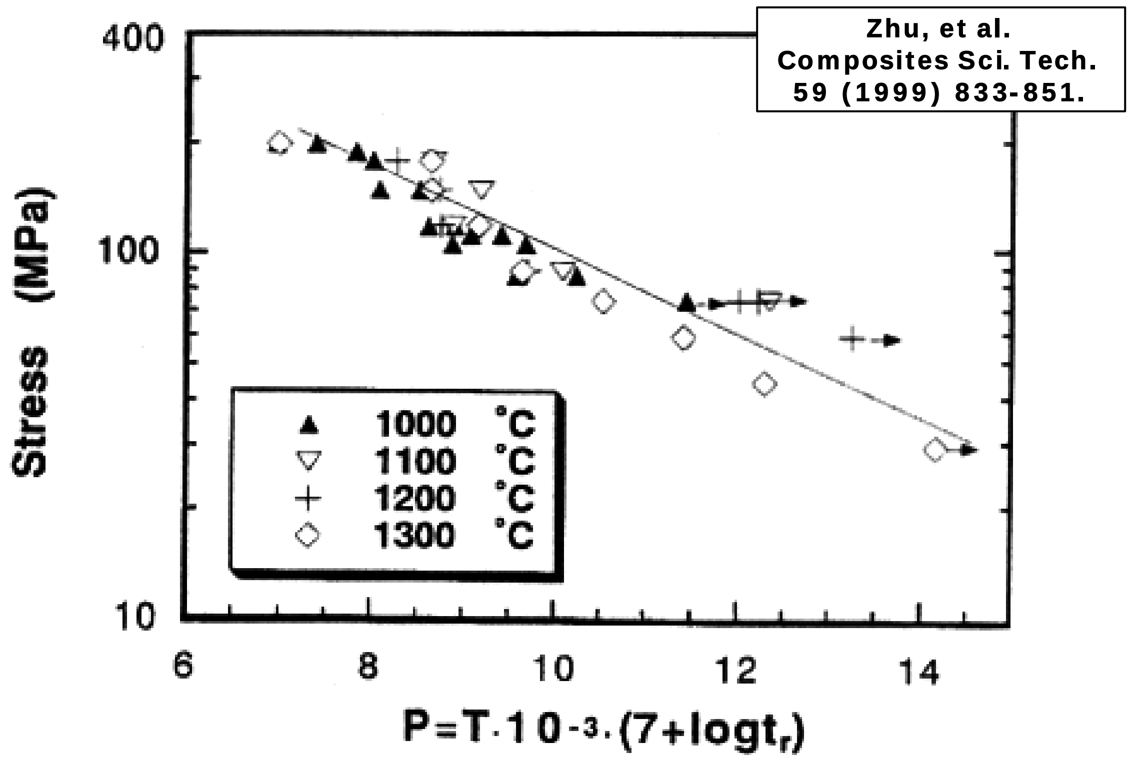
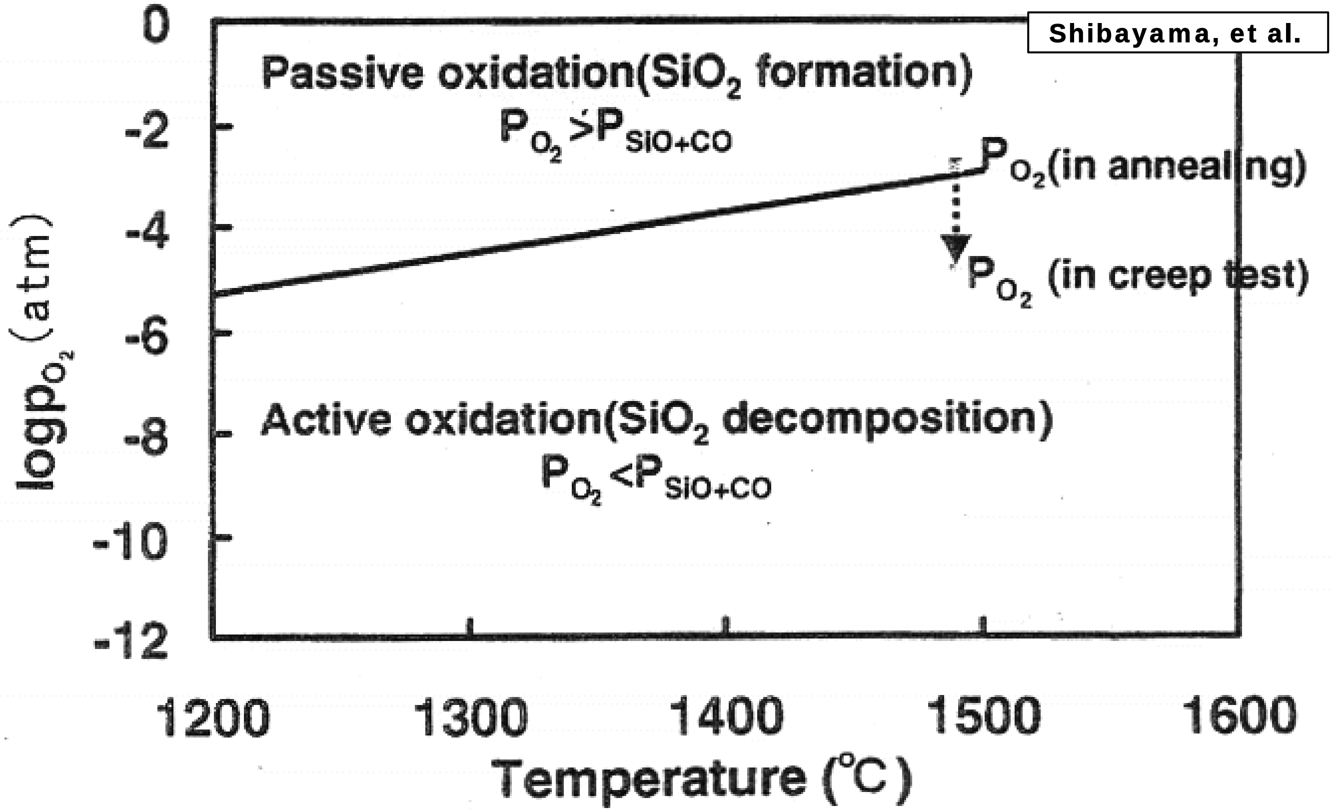


Fig. 17. Tensile stress versus Larson–Miller parameter at different stresses in argon at 1000, 1100, 1200 and 1300°C.

- Larson-Miller approach may be applicable to stress-rupture time prediction.

Oxidation Behavior of SiC

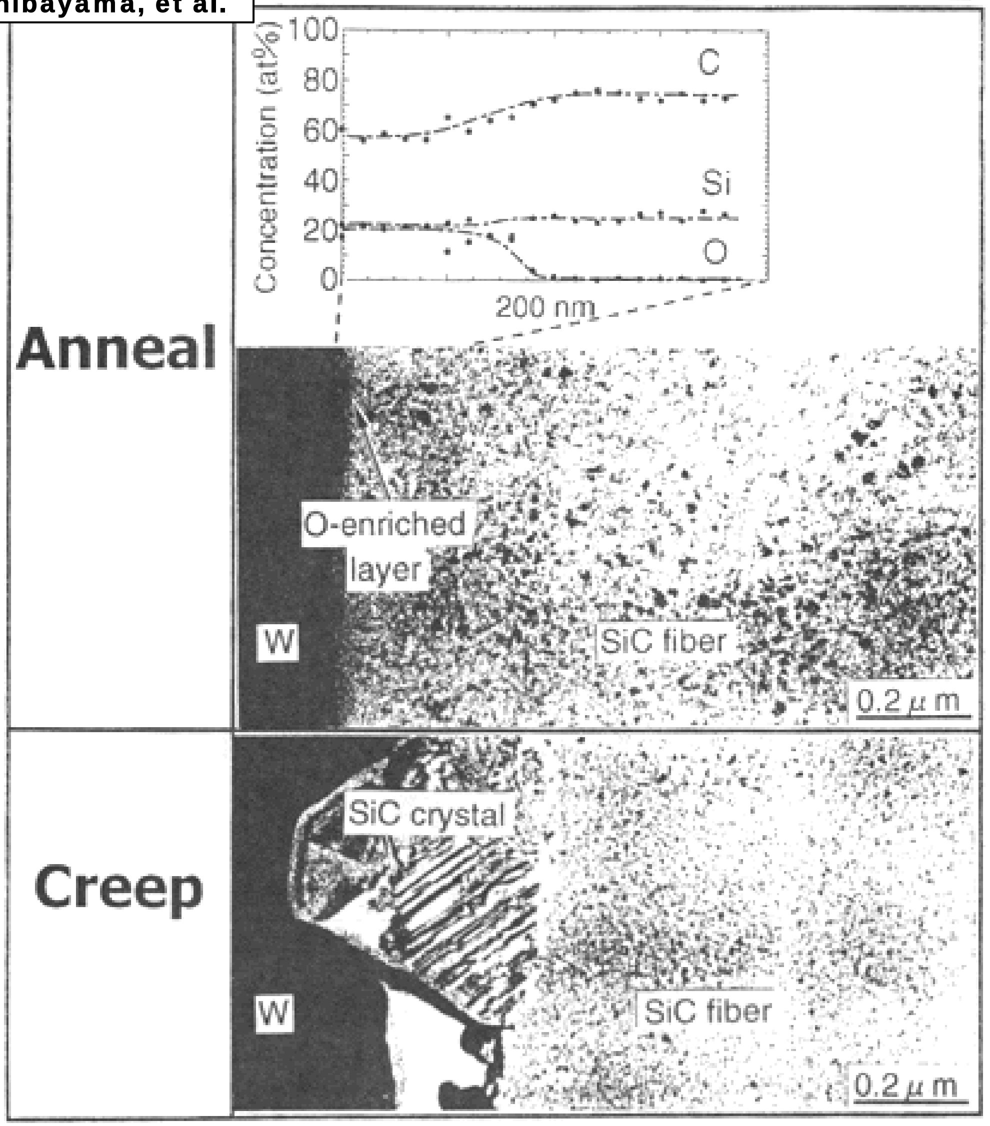


* Earl A. Gulbransen and Sven A. Jansson: Oxidation of Metals. 4 pp.181-201 (1972).

- Commercial Ar: O_2 <10ppm (normal grade), O_2 <1ppm (high purity), O_2 <0.2ppm (semiconductor process grade)

Effect of Tensile Stress on Erosion Behavior

Shibayama, et al.



- Erosion behavior of Hi-Nicalon fiber under tensile stress is dissimilar to that in stress-free state.
- Creep and fatigue behavior in nominally ‘passive oxidation’ environment may be complex.
- Advanced fibers are expected to exhibit improved stability.

TEM images and SAD patterns for Hi-NL Type-S composite

Single-beam

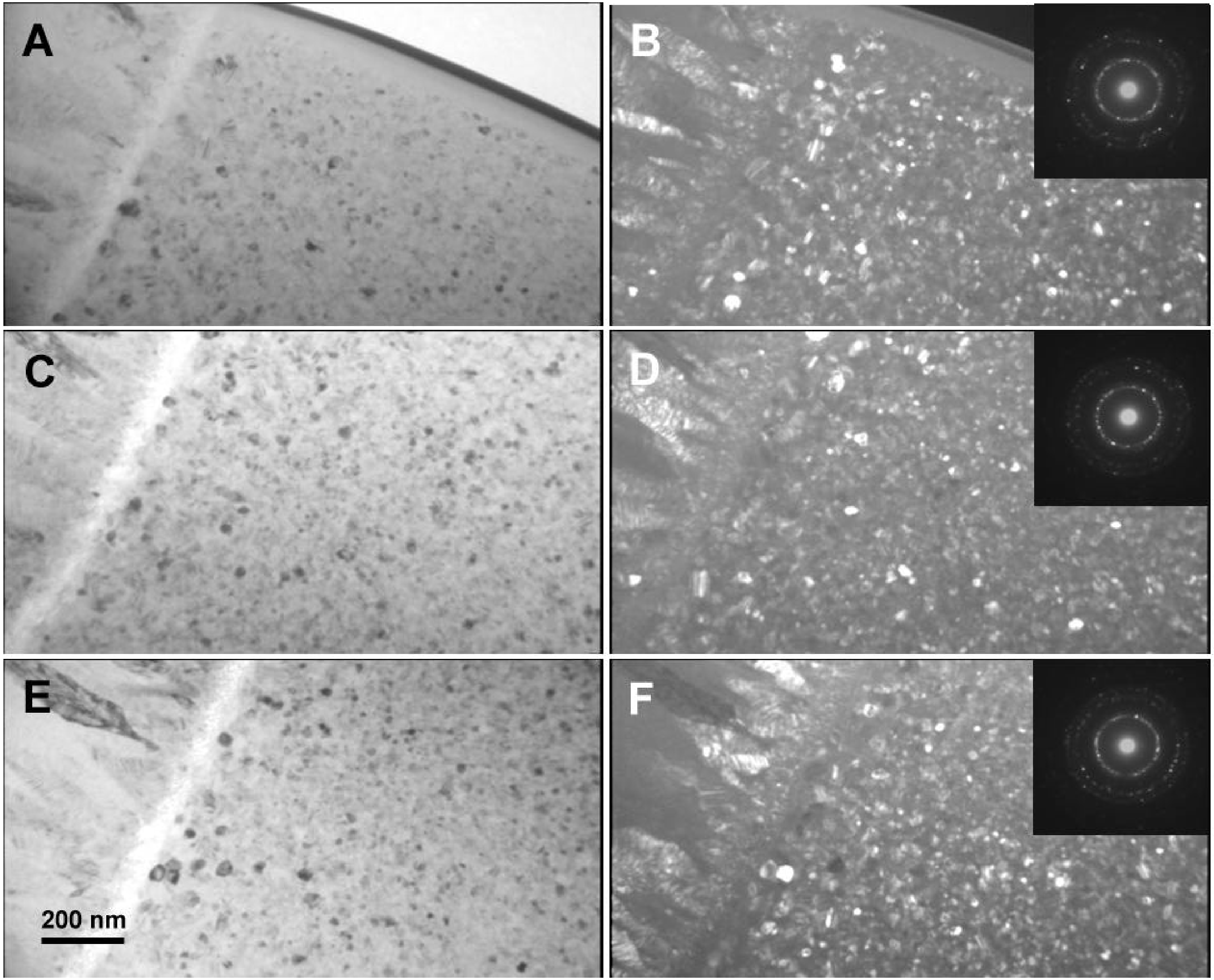
10dpa
873K
$1X10^{-3}$dpa/s

Dual-beam

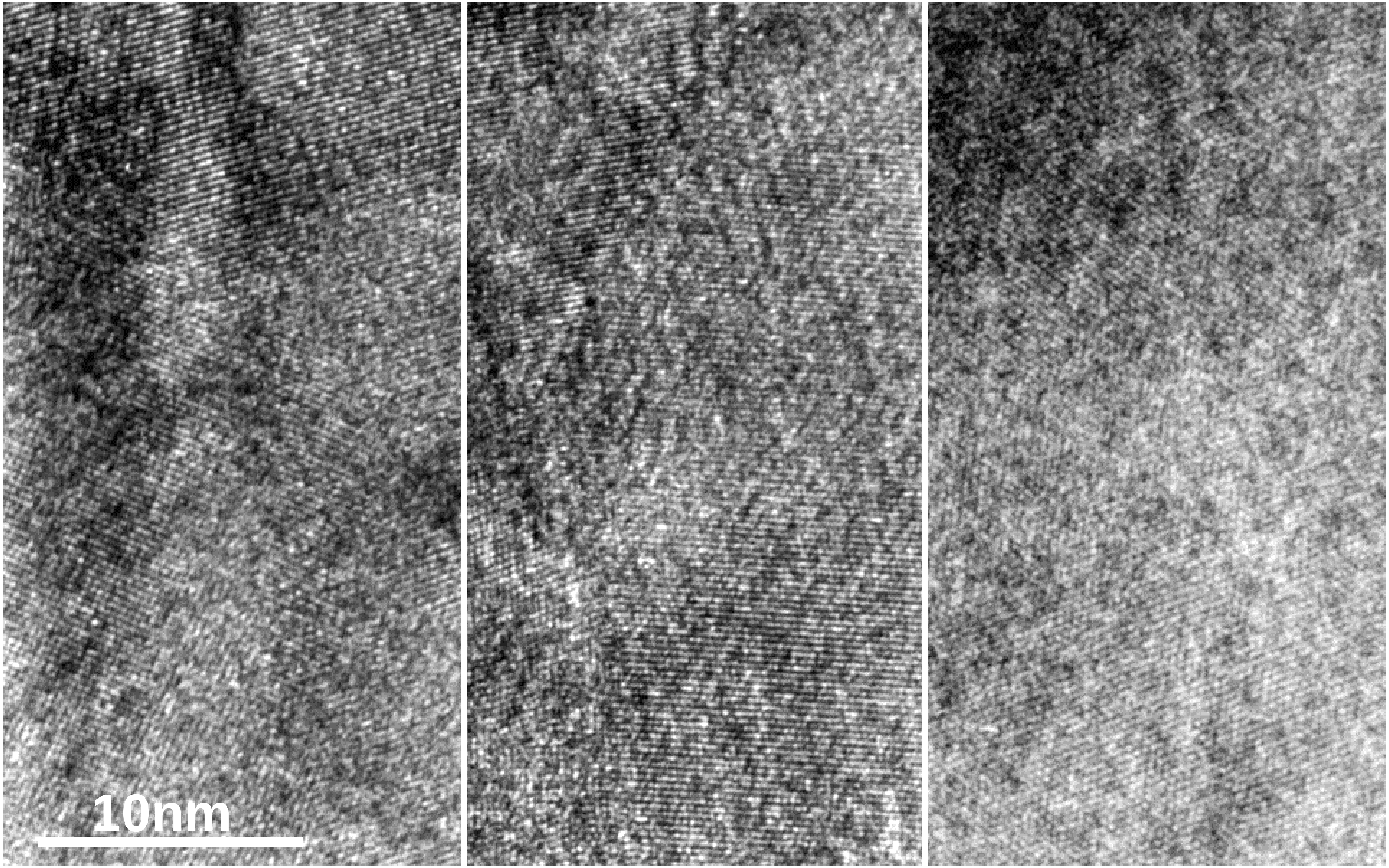
10dpa
873K
$1X10^{-3}$dpa/s
60appm-He/dpa

Unirradiated

Dark field images from SiC <111> diffraction rings.

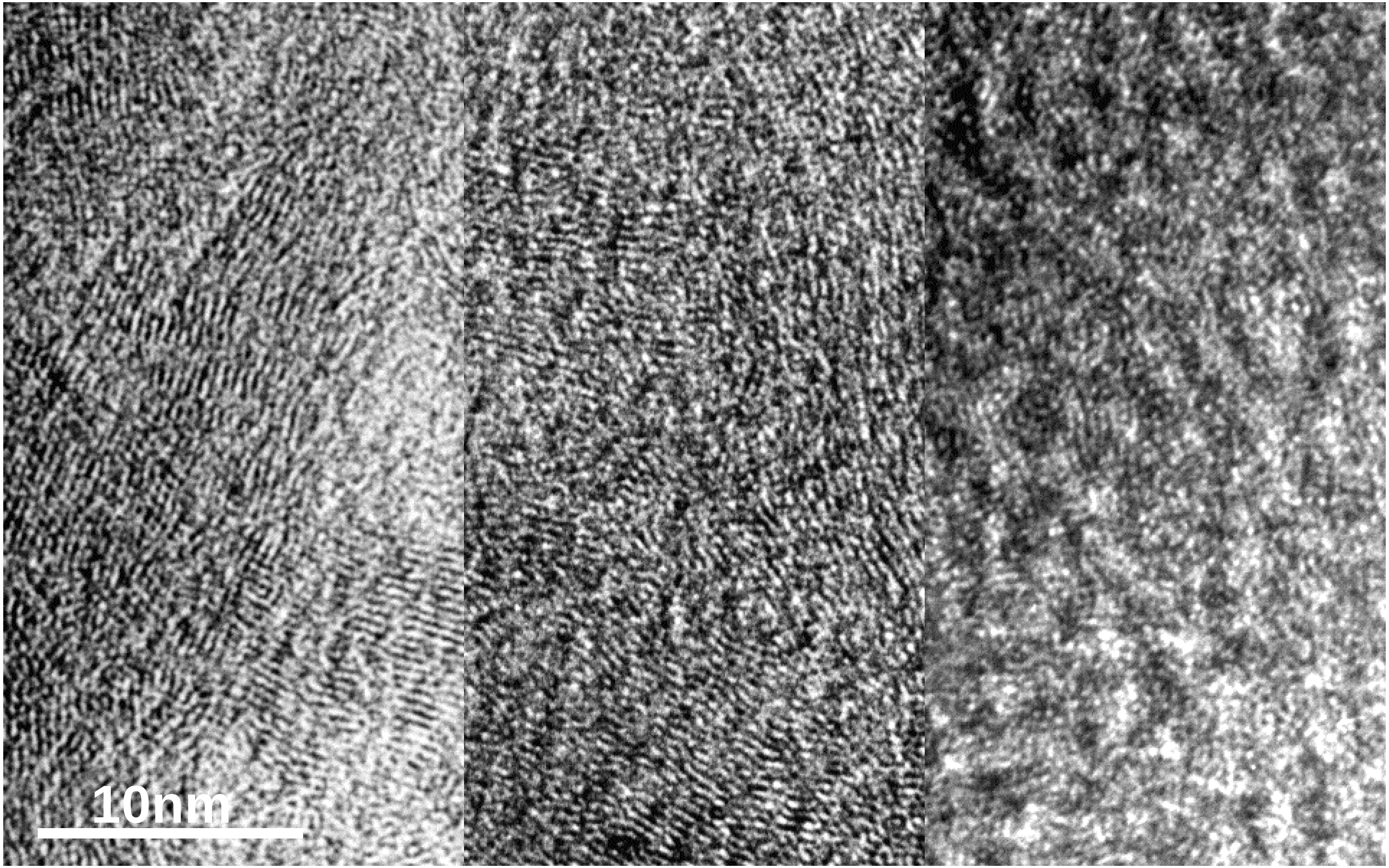


As-CVI'ed and Ion-Irradiated Hi-NicalonÒ Type-S



Unirradiated | Single-beam irradiated | Dual-beam irradiated

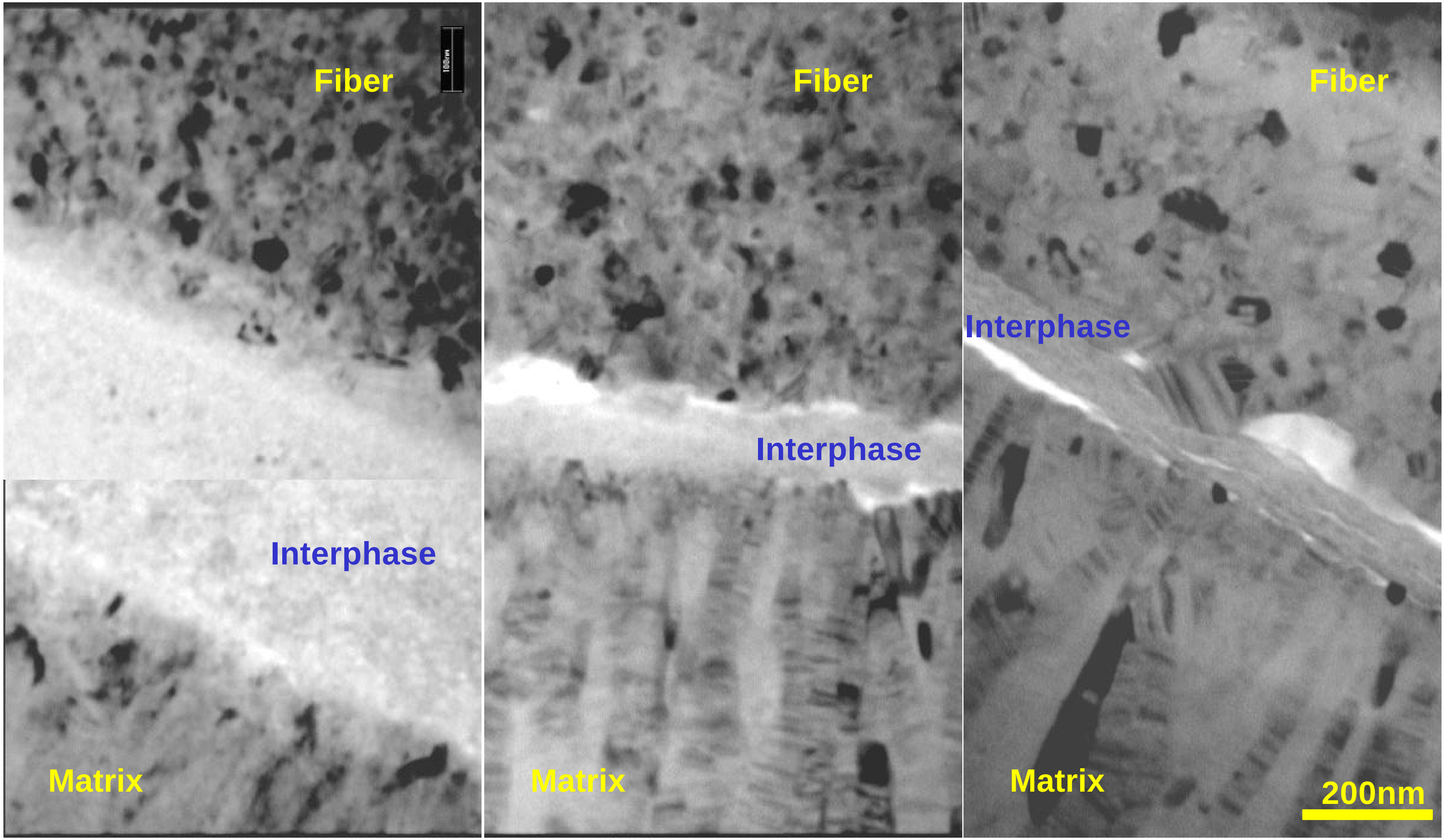
As-CVI'ed and Ion-Irradiated Pyrolytic Carbon Interphase



Unirradiated Single-beam irradiated Dual-beam irradiated

Structural Instability of SiC at F-M Interfaces

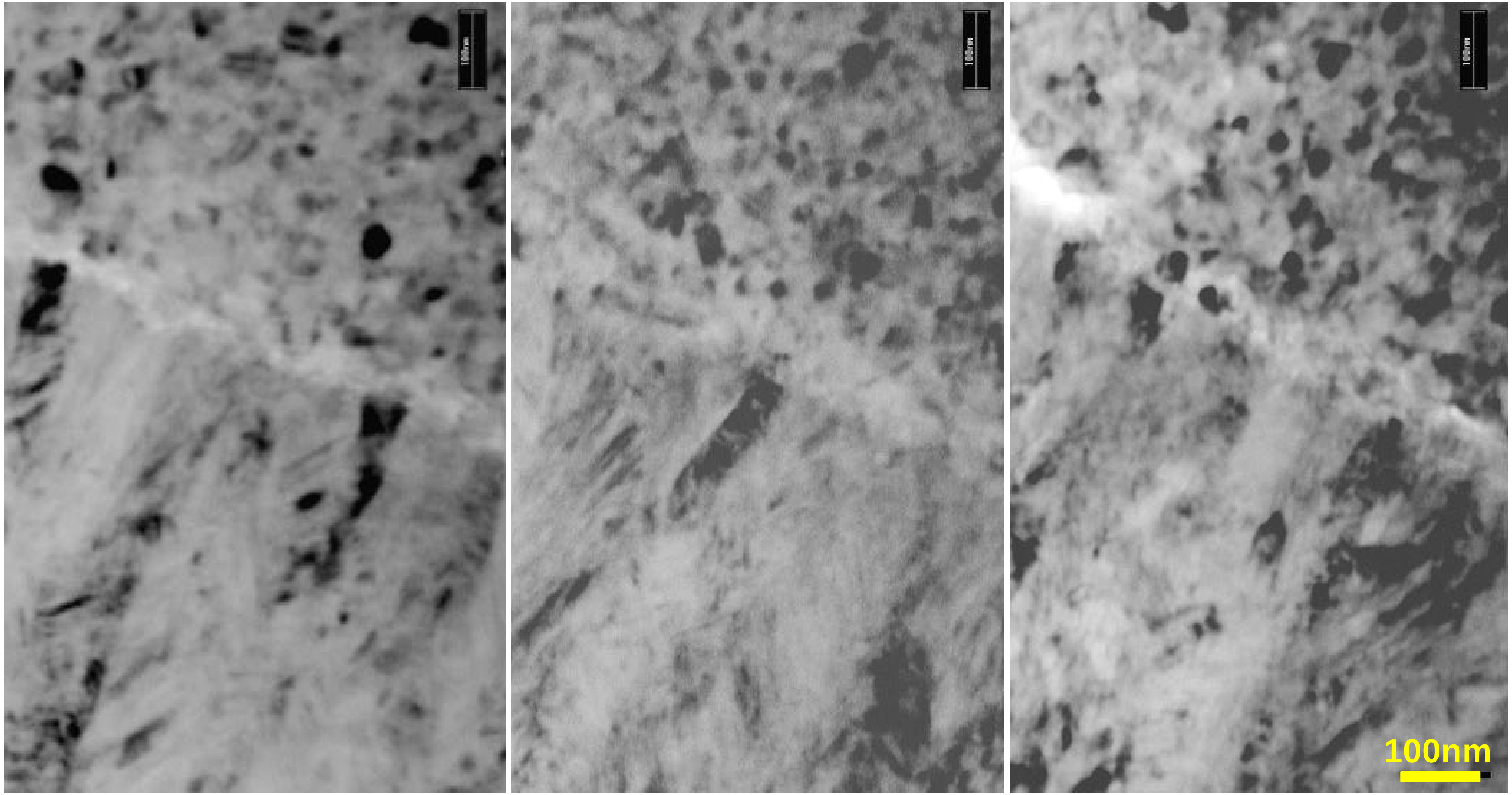
Hi-Nicalon Type-S / PyC / CVI-SiC Composite



Annealed at 1473K for 3600s **Annealed at 1673K for 3600s** **Annealed at 1873K for 3600s**

Structural Instability of Hi-NL at Interfaces

Annealed at T for 3600s following dual-ion irradiation to 10dpa at 873K



T = 1073K **T = 1273K** **T = 1473K**

Low Temperature Swelling

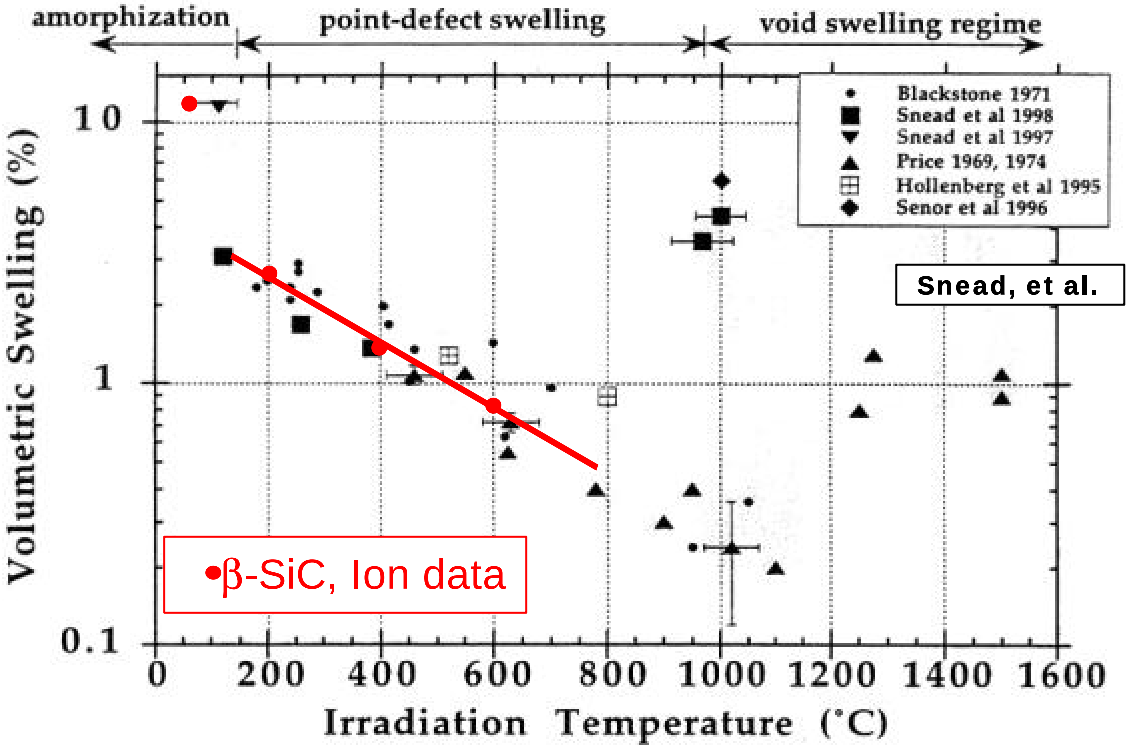
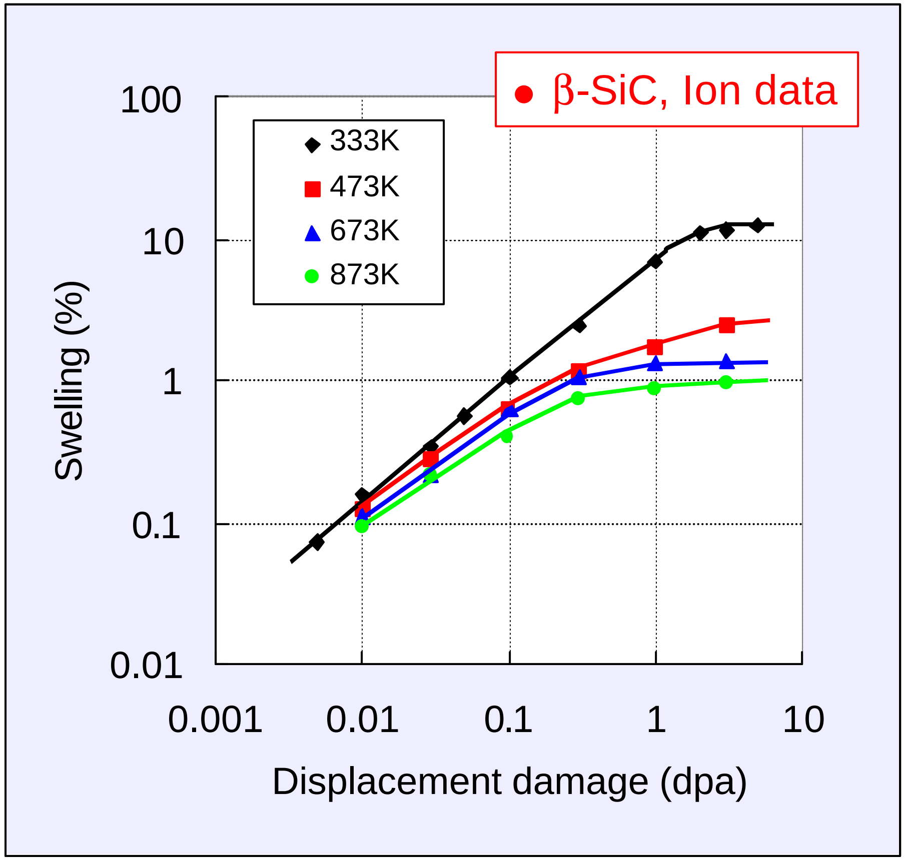


Fig. 3. Radiation induced swelling in bulk SiC as a function of irradiation temperature [6,14,26-29].

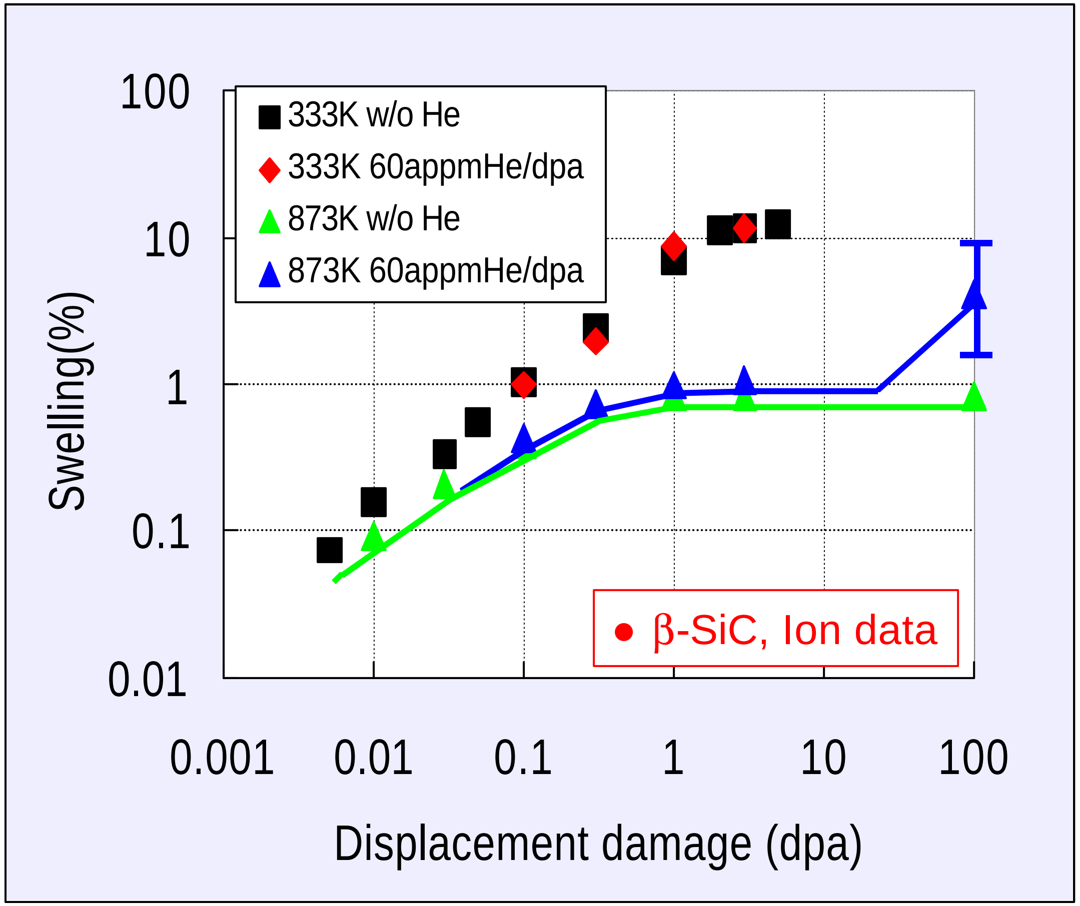
- Low temperature swelling seems to have been well characterized.
- Neutron data may be affected by uncertainty and transient effect of irradiation temperature. Ion irradiation experiments will confirm it under accurate temperature control.

Low Temperature Swelling



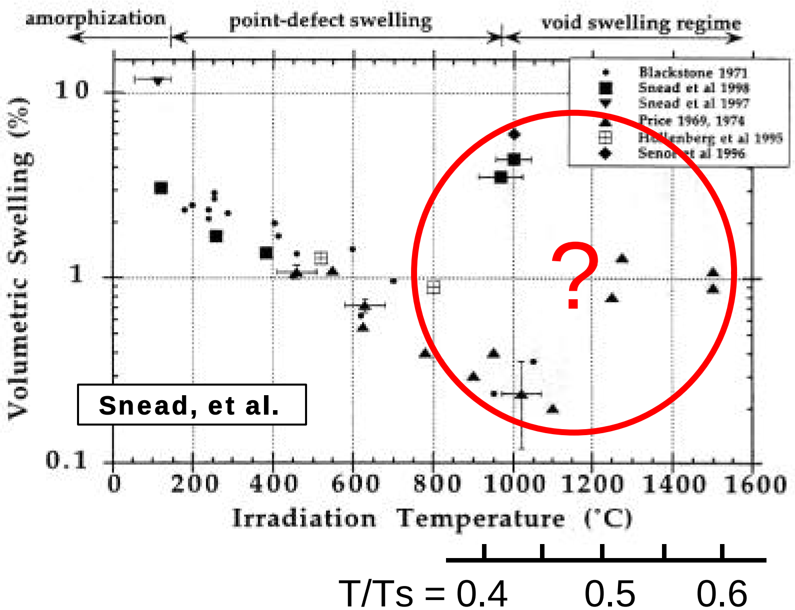
- Low temperature swelling due to point defect accumulation may exceed 1% at temperatures below 673K.
- Low temperature swelling saturates in helium free conditions. Saturation behavior is highly predictable.

Helium Effect on Low Temperature Swelling



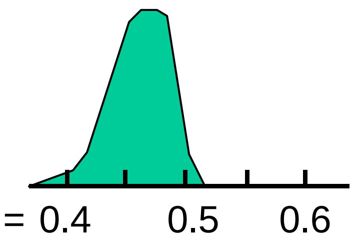
- Helium accumulation alters the state of point defects (and clusters) once saturated by lower doses at low temperatures.

High Temperature Swelling



[6,14,26-

Swelling trend of stainless steels in fast reactors



- We know very little about the high temperature swelling behavior of SiC.
- Transmutant helium will play the key role.
- Dual-beam ion irradiation experiment is needed to explore the synergistic effect of high-fluence irradiation and helium production.

Helium Effects on Mechanical Properties

- Helium accumulation in crystal grains:
  - Effect of swelling
- Helium precipitation in grain boundaries
  - Fracture energy degradation?
- Helium agglomeration at F-M I/F:
  - F-M debonding
  - Enhanced amorphization of carbon interphase

Irradiation Effects on F-M Interface Integrity

- **Amorphization of carbon**
  - Anisotropic swelling of oriented graphitic carbon
  - Isotropic swelling of glassy carbon
  - Strength degradation of interphase itself
  - Bonding strength degradation
- **SiC crystal growth at boundaries due to chemical instability**
  - Debonding at C/SiC boundaries
  - Sliding stress increase
- **Helium effect**
  - Potential helium bubble precipitation
  - Other unknown effects?

Summary

- Limited amount of data on fatigue, thermal creep and erosion behavior are available for older generation SiC/SiC.
- Neutron-related lifetime limiting issues are not sufficiently identified for SiC/SiC composites for fusion blanket applications.
- These properties of ‘fusion grade’ SiC/SiC need to be characterized. It is expected that the performances of fusion grade SiC/SiC largely exceeds those of conventional materials.