Materials & Design Issues for Joining SiC Composites for Fusion Energy

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Primary goals for the use of SiC/SiC in fusion energy

- **Low residual radioactivity to minimize:**
  - **risk to workers**
  - **contamination in the event of accidents**
  - **environmental impact of waste disposal**
- **Mechanical reliability**
- **Microstructural stability during irradiation of:**
  - **fibers**
  - **interphases**
  - **matrix**
- **Minimal gaseous transmutation**
- **Hermetic behavior**

Critical materials requirements for joining SiC/SiC for fusion energy

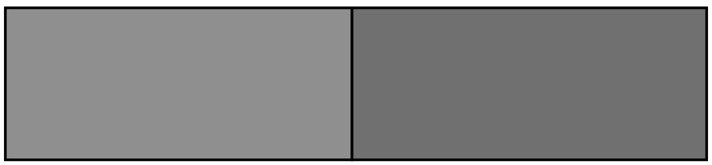
- **Mechanical properties**
- **Thermal expansion match**
- **Radiation/Chemical stability**
- **Thermal conductivity**
- **Time-dependent properties**
- **Hermeticity**

Design requirements for joining SiC/SiC for fusion energy

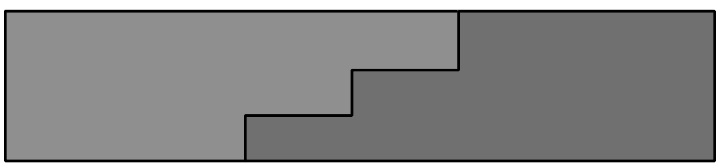
- **Thermo-mechanical stress state**
  - **Low shear stresses : in-plane and through thickness**
  - **Minimal thermal gradients**
  - **Principal stresses below matrix cracking stress (?)**

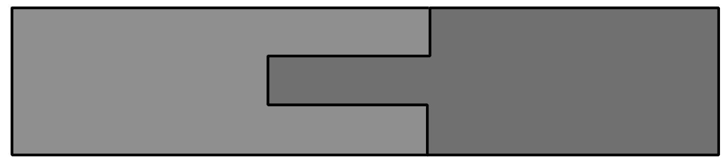
- **Field assembly**
  - **Compatible with processing and machining techniques**
  - **Assemblage under ambient conditions**
  - **Practical for 1 m scale components**
  - **Hermeticity**

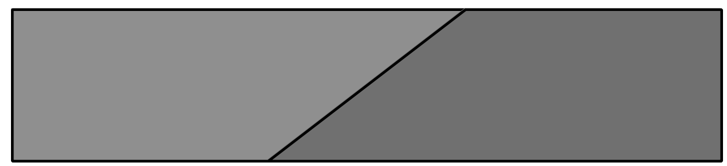
Illustrative joint designs for SiC/SiC

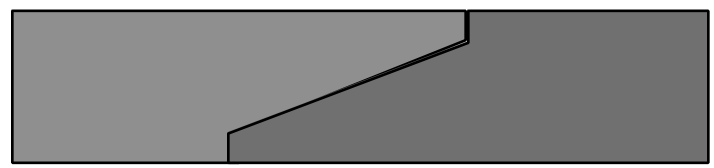

Butt joint


Lap joint


Double Lap joint


Mortise and Tenon joint


Tapered butt joint


Tapered Lap joint

Some critical issues in joint durability

For a given joint design:

- **Strength of joint material vs.matrix**
- **Stability of matrix and fibers**
- **Radiation effects on joint materials**
- **Thermal cycling effects**
- **Differential creep effects**

Physical parameters required for materials R&D

- **Stress-state**
  - **Principal stresses, bending moments, shear stresses**
  - **Temporal behavior (fatigue, TMF)**
- **Temperature**
  - **Gradients**
  - **Temporal behavior**
- **Chemical environment**
  - **Oxygen content**
  - **He pressure**
  - **Coolant composition, temperature, pressure**
- **Neutron flux**
- **Plasma-surface interactions**
  - **Particle momentum**
  - **Particle elastic properties**

Candidate joint materials for use in Fusion Energy Systems

- **Melt infiltrated and reaction-formed silicon carbide.**
- **Preceramic-polymer derived silicon carbide.**
- Low-activation, high-temperature glasses.
- In-situ reinforced silicides.
- High-temperature brazes.

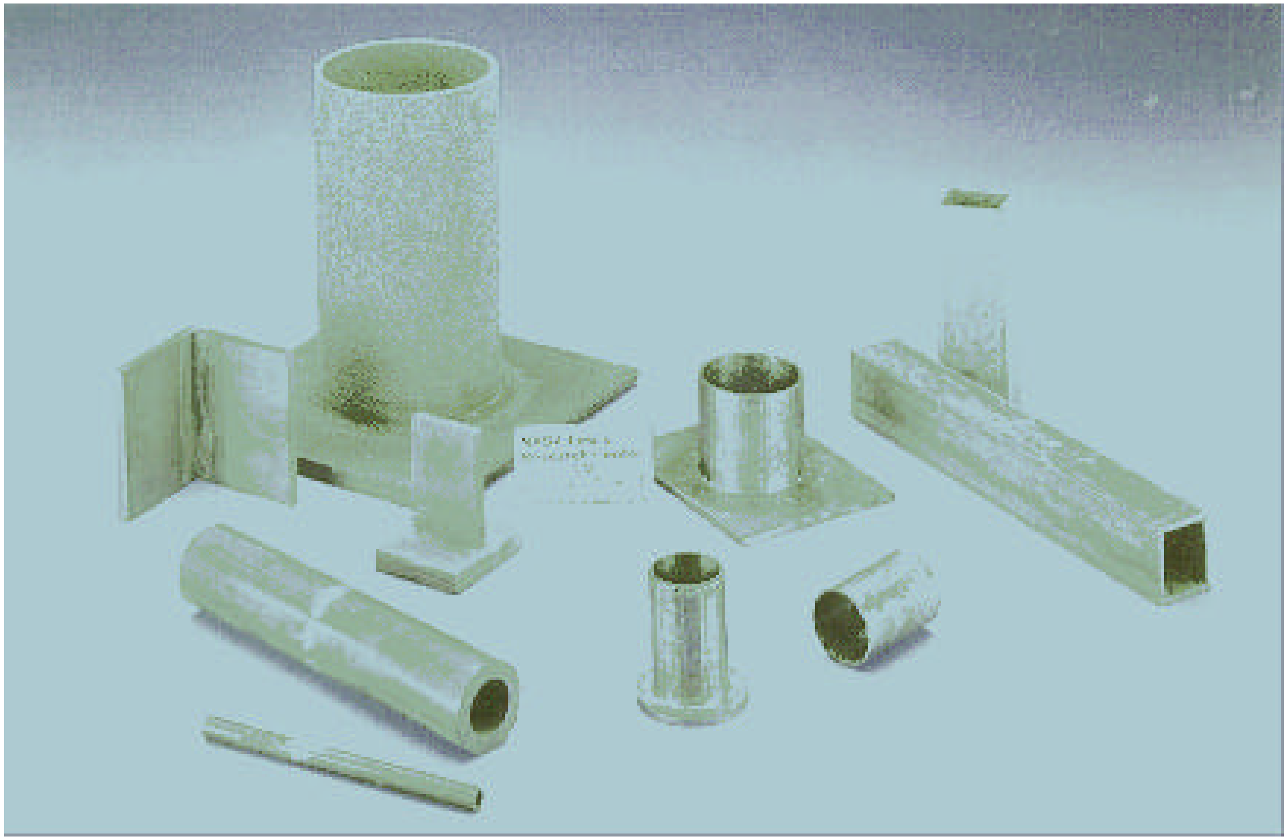
Material studied

- ***Reaction Formed Silicon Carbide*: silicon carbide formed by reaction of a carbonaceous structure with molten silicon or silicon alloys. Fabricated using the ARCJoinT process developed at NASA Glenn Research Center.**
- ***Reaction Bonded Silicon Carbide*: particulate silicon carbide bonded by silicon carbide formed by reaction of carbon powders with molten silicon. Fabricated by BUSEK Co., Inc., Natick, MA.**

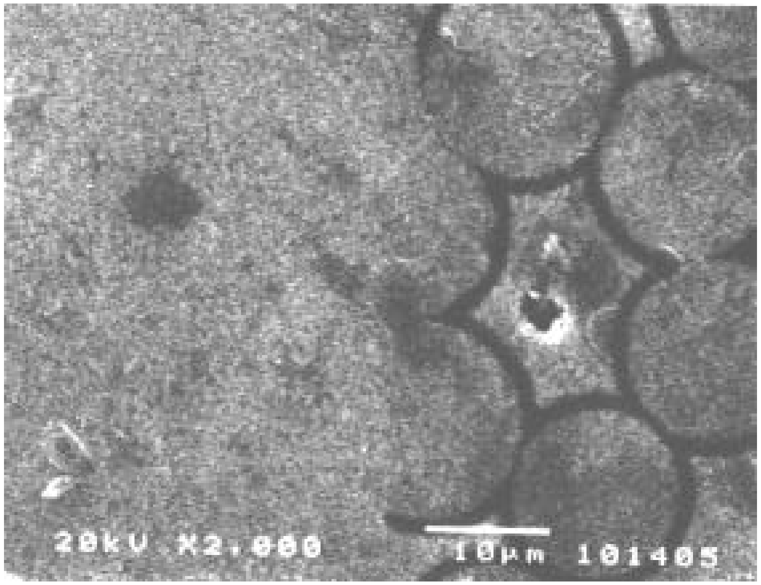
Material studied

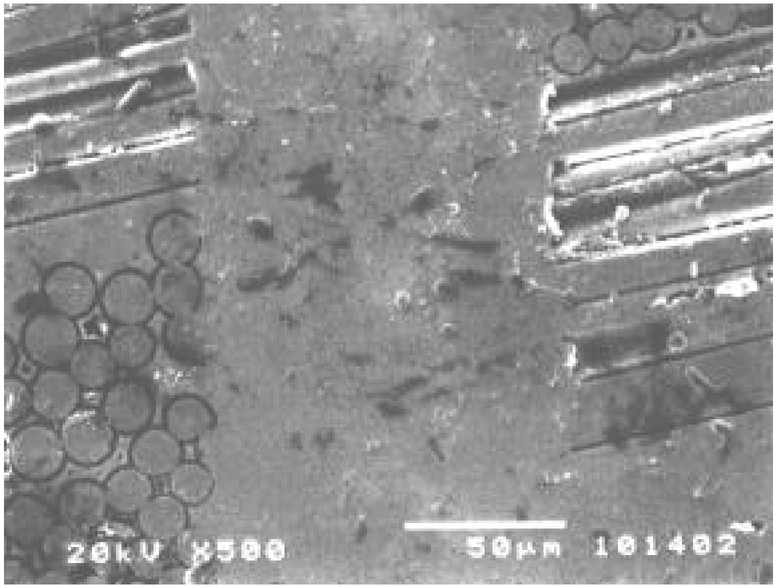
- Substrates:
  - ***Hexoloy SA*: monolithic, sintered, alpha SiC. Approximate grain size 2-3 μm.**
  - ***Hi-Nicalon reinforced, CVI silicon carbide*: 40 vol. % fibers, 0/90º plain-weave**.

Reaction-formed silicon carbide is a promising joint material



Interfacial reactions must be studied



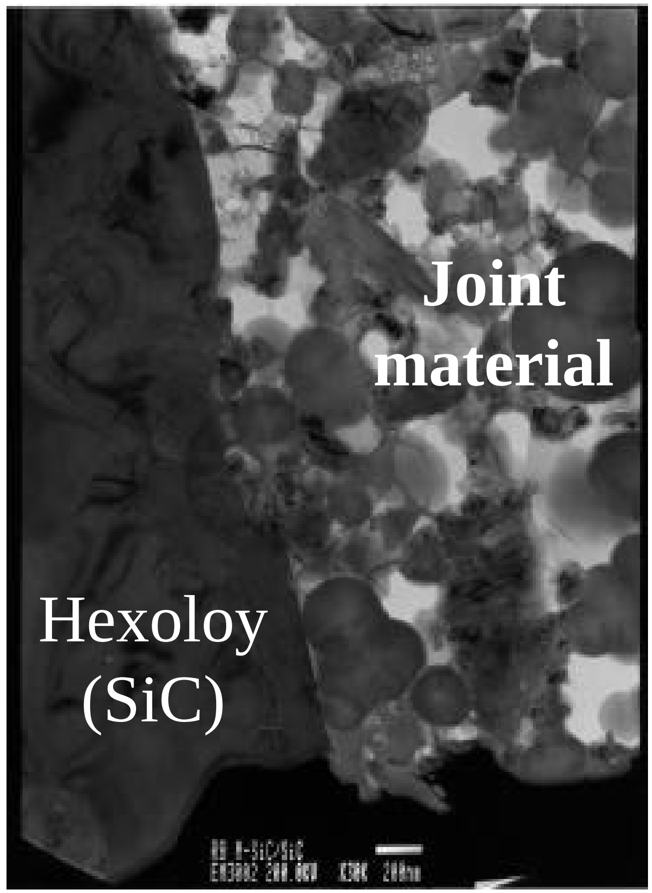


Long-term compatibility between joint material and composites must be investigated

Effects of microstructural evolution

- **Interface reactions may lead to brittle phases or composite damage**
- **Time dependent properties may occur due to chemical diffusion:**
  - **Thermal Expansion**
  - **Elastic Moduli**
  - **Shear Strength**
  - **Stress distribution**

Microscopy may be used to examine interfacial reactions



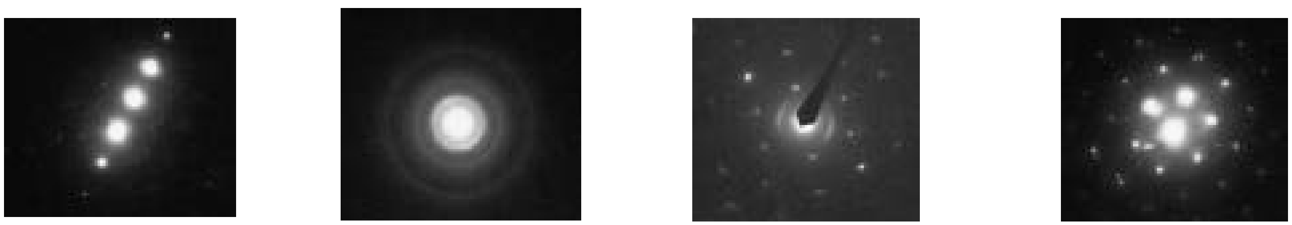
Untreated joint appears micro-crystalline

HRTEM used to determine phase distribution

***In practice*, joints must be made in the field.**

Joining conditions: 1250-1425 C
5-10 min
no external pressure

SiC C Interface Hexoloy SA

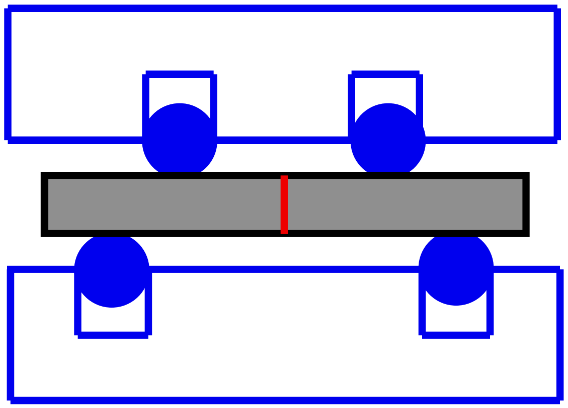


(Selected area diffraction patterns [SADP])

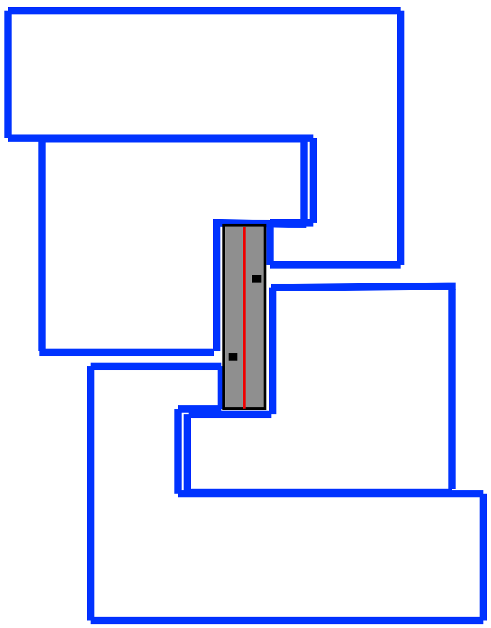
Control of spatial phase distribution may allow functional grading of thermomechanical properties.

Mechanical Testing

Maximum Tensile
<u>Stress</u>
4-pt bending

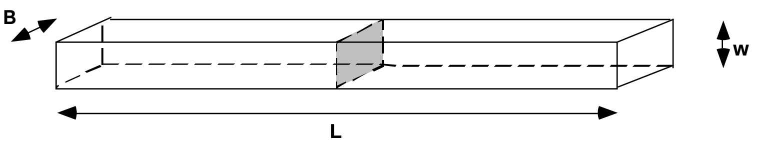


In-plane
<u>Shear Stress</u>
Double-notch-shear in compression

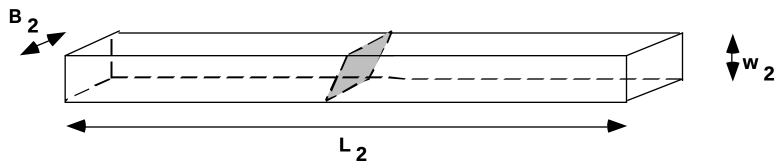


Mechanical Testing

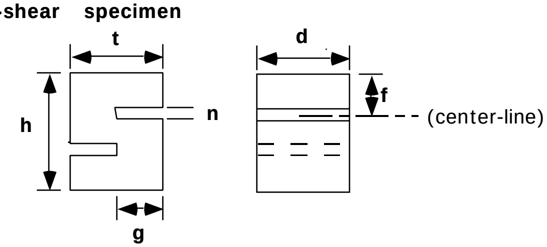
Butt-joined flexural test specimen



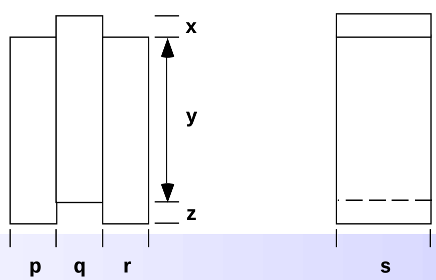
45° Butt-joined flexural test specimen



Double-notch-shear specimen



Offset sandwich specimen

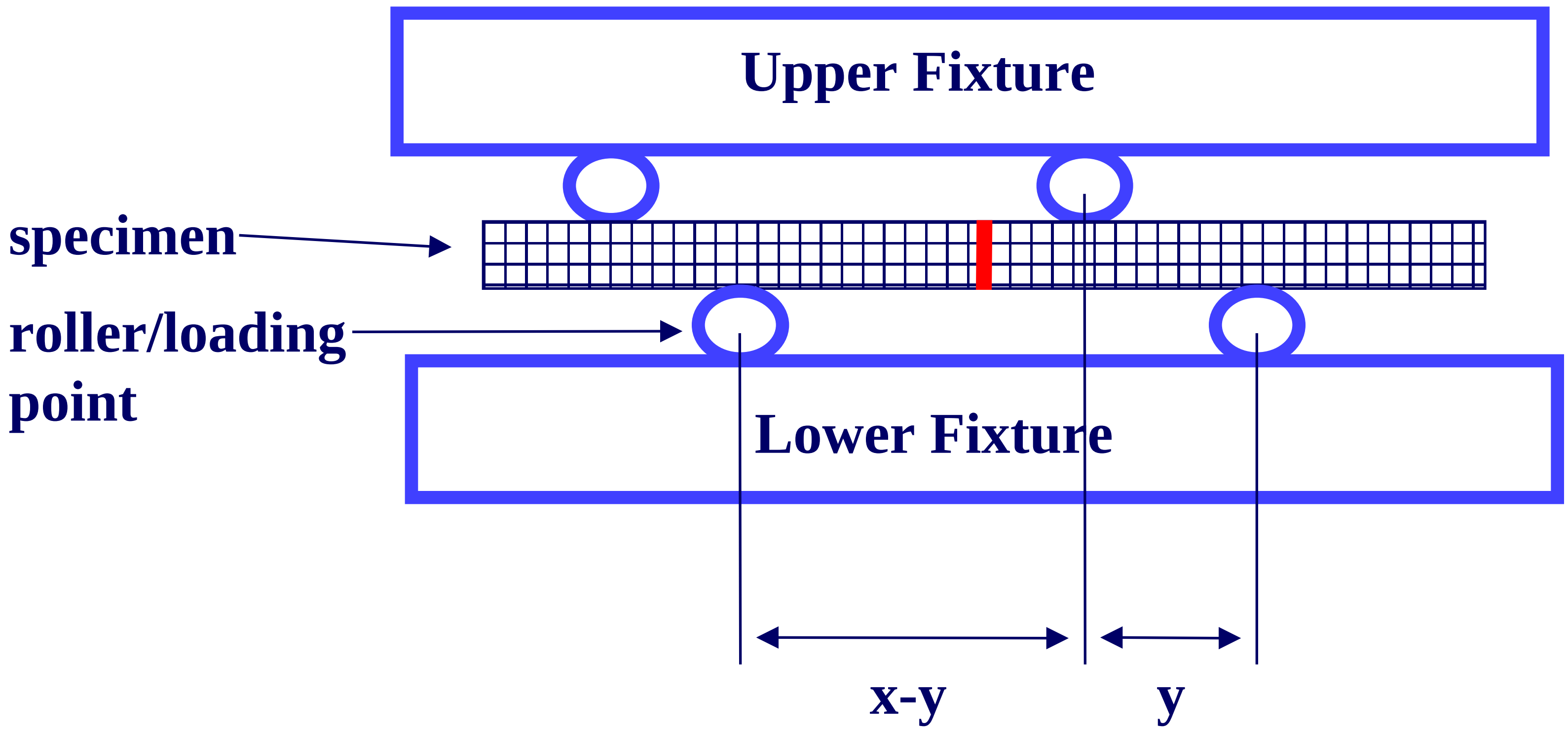


not drawn to scale.

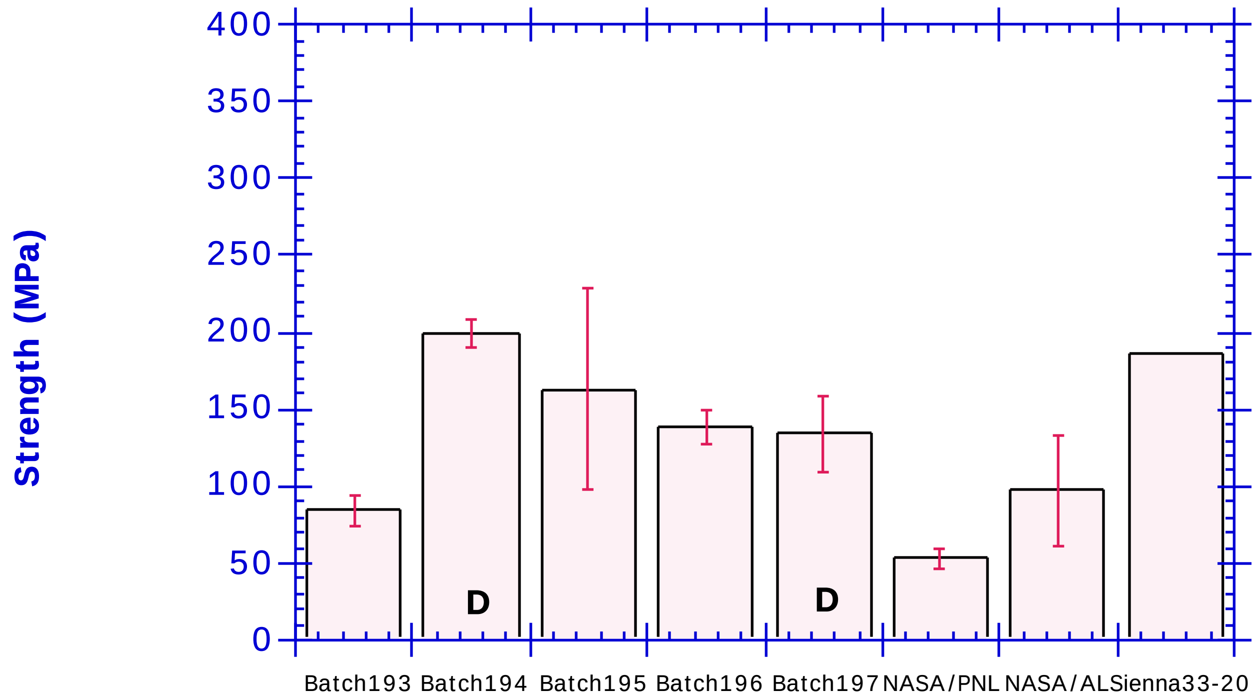
Mechanical Testing

Through Thickness Shear Stress

Asymmetric 4-pt bending

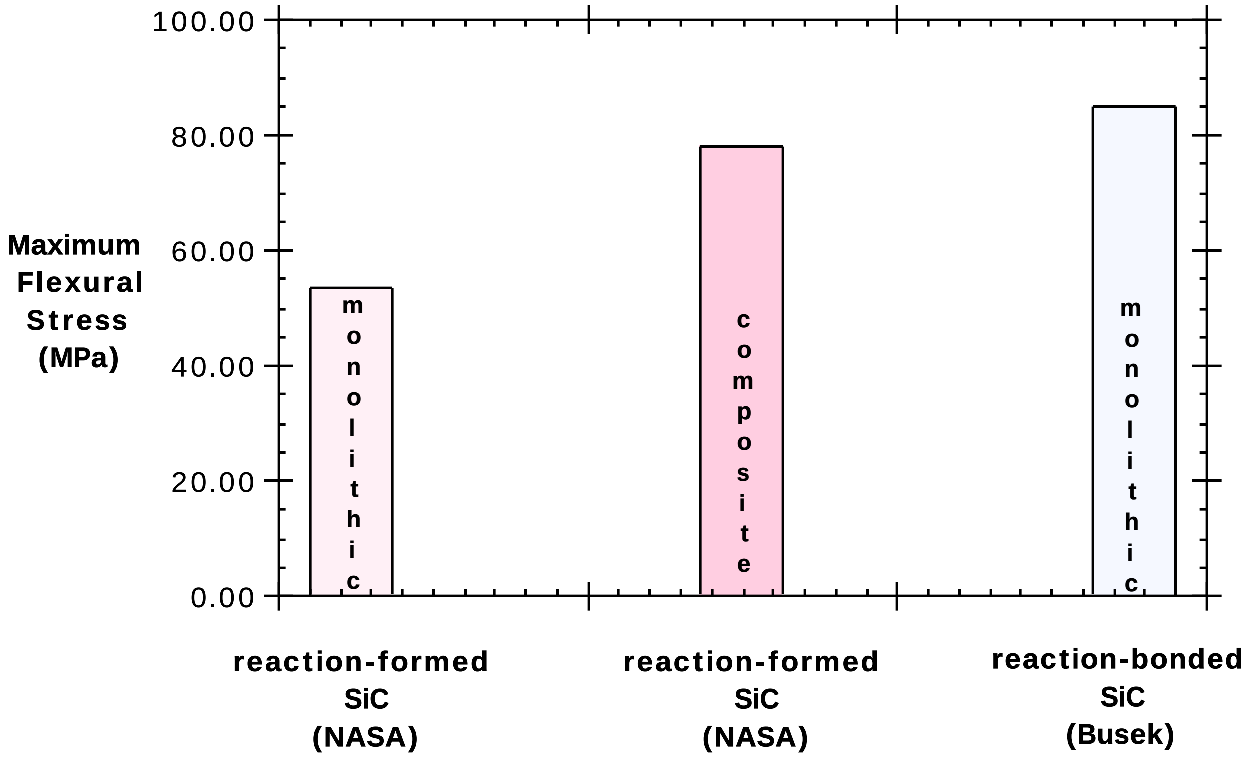


Results: Flexural Strength



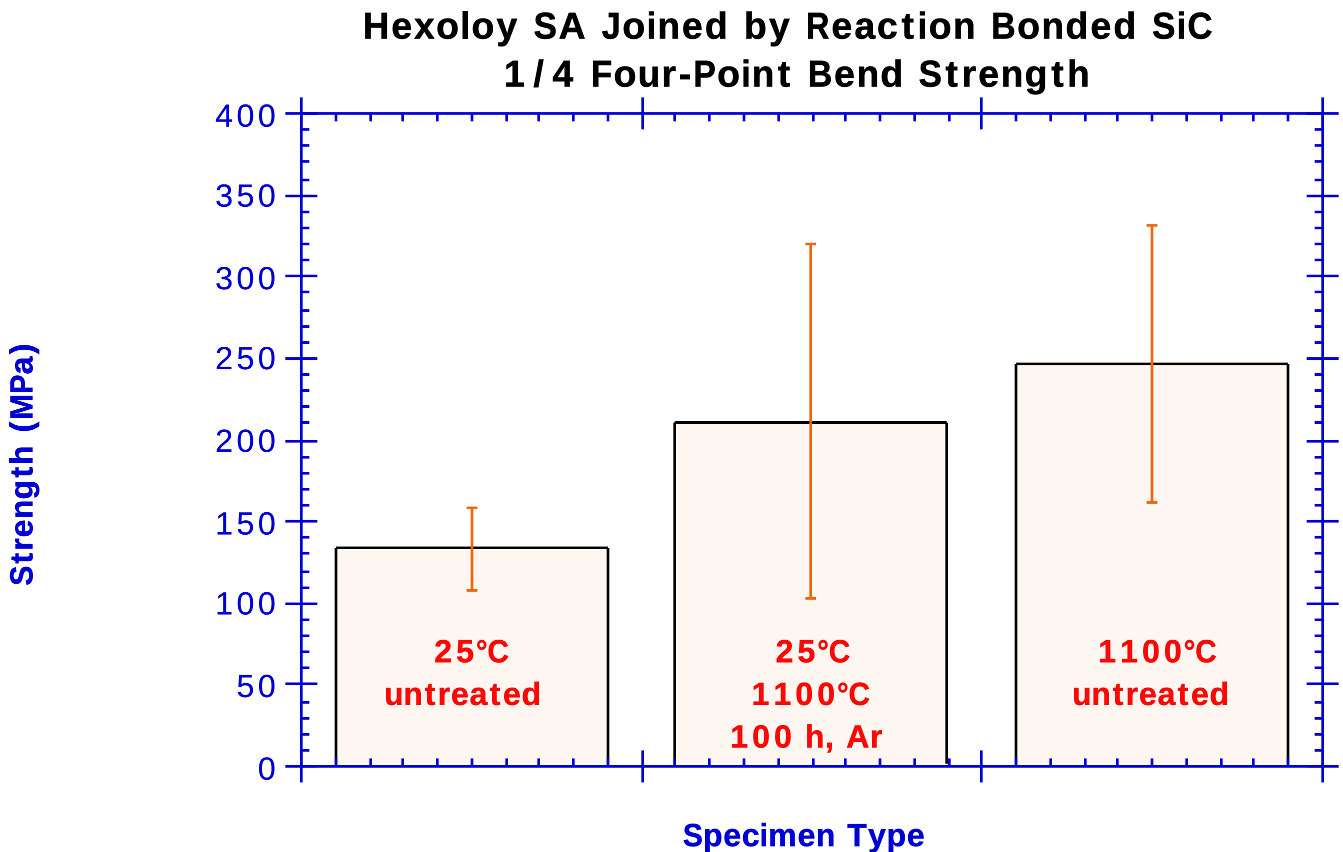
- **Four-point bend strengths on the order of 200-300 MPa are commonly reported**

Results: Flexural Strength



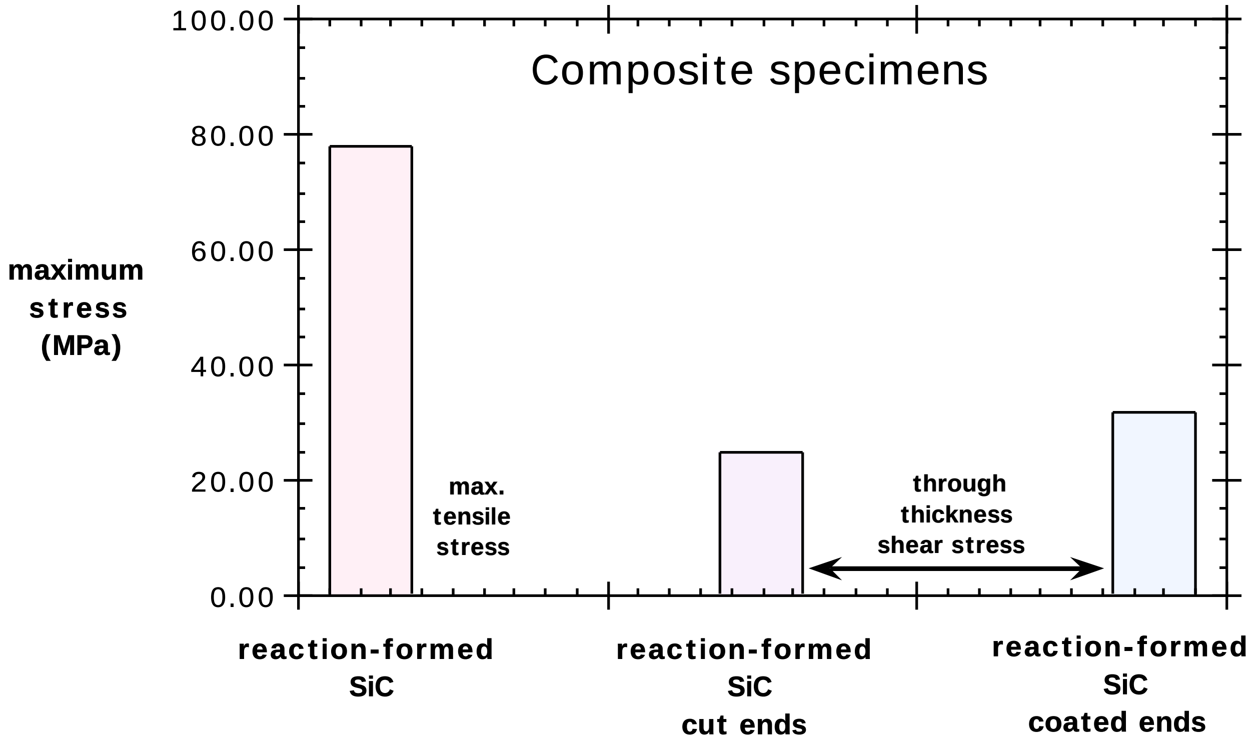
✷Bond strengths for composite substrates were in the range of those for monolithic substrates.

Results: Flexural Strength



✶**Additional heat treatment improves flexural strength.**

Results: Through-thickness shear strength



✶The value of the Through-Thickness Shear Strength was similar for composites joined at cut surfaces or surfaces coated with CVD-SiC.

Results

Substrate	Joint Material	Test Method	Test Temp. (K)	Joint Thickness (μm)	Strength (MPa)
RBSC	RFSC	4PBS	298	10	210 $\pm$ 6
Hexoloy SA	RFSC	4PBS	298	45-50	255 $\pm$ 3.2
Hexoloy SA	RFSC	4PBS	298	52	53 $\pm$ 6
Hexoloy SA	RBSC	4PBS	298	130	85 $\pm$ 10
SiC_f/SiC_m	RFSC	A4PB	298	115	28 $\pm$ 7
SiC_f/SiC_m	RFSC	4PBS	298	115	78 $\pm$ 8
SiC_f/SiC_m	RFSC	4PBS	298	125	65 $\pm$ 5
SiC_f/SiC_m	RFSC	4PBS	1073	125	66 $\pm$ 9
SiC_f/SiC_m	RFSC	4PBS	1473	125	59 $\pm$ 7

RBSC = reaction-bonded silicon carbide
RFSC = reaction-formed silicon carbide
4PBS = 1/4, four-point bend strength
A4PB = assymmetrical, four-point bend strength

Summary

- **Materials issues: radiation stability, physical properties, hermeticity.**
- **Design issues: thermomechanical stresses, field assembly.**
- **Critical issues: time-dependent properties, radiation effects, thermal cycling, differential creep.**
- **Materials studied: reaction-formed and reaction-bonded SiC.**
- **Results:**
  - **Flexural strengths around 200 MPa were obtained.**
  - **Flexural strengths were independent of substrate material.**
  - **Additional heat treatment improved the flexural strengths.**
  - **Through-thickness shear strengths of joint materials were lower than the tensile strengths, but were not dependent on the surface treatment.**

Future work

- Optimize joint processing conditions and thickness for mechanical properties.
- Study effects of thermal exposure and irradiation on microstructure and properties.
- Evaluate mechanical test methodology for irradiation studies.
- Investigate stress distribution in realistic joint geometries via FEM modeling.