# Joining of SiC Components and Evaluation of Joint Characteristics*

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*Supported by DoE SBIR Grant

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Presentation at PFC 2004 Workshop at UIUC, May 5, 2004

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# Outline

• Overview of Joining Efforts at FM Technologies, Inc. (FMT)

• FMT's Joining Scheme for SiC Components

• Joining Tasks with $SiC_f/SiC_m$ Composite (including results on $C_f/SiC_m$ composite joining)

⇨Optimization of Geometry of Joining Coupons (experiments and modeling)

⇨Optimization of Processing Steps: rapid, reliable joints

⇨Mechanical Characteristics: flexure strength, failure studies – fractographic analysis (optical microscopy and SEM), XRD analysis of joining areas.

• Highlights of Phase I Achievements and Phase II Plan

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# Overview of Joining Efforts at FM Technologies, Inc. (FMT)

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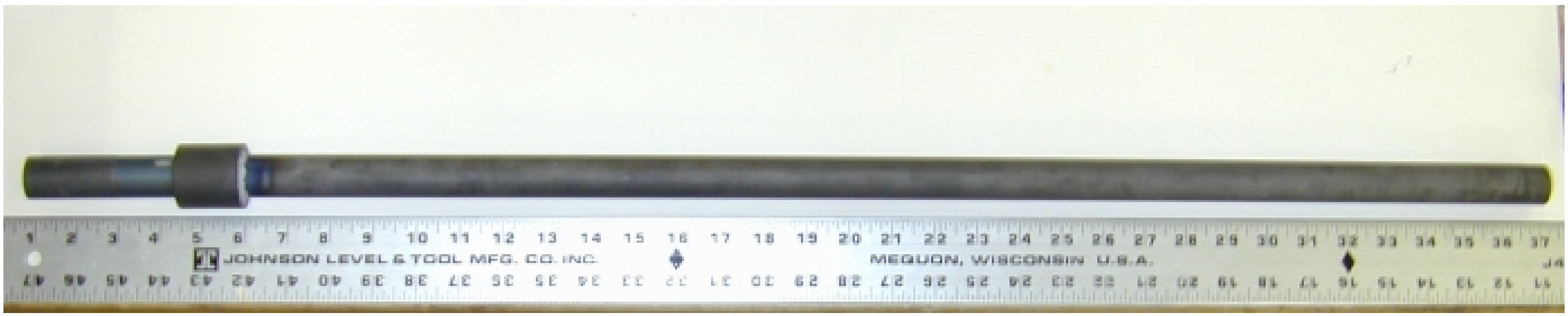
# Joining of Sintered SiC Tubes




Applications: Furnace coils for the ethylene industry, retorts for the chemical industry

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# Joining of Reaction-Bonded SiC Tubes

Applications: Radiant burner tubes for metal heat-treating, high-temperature heat exchangers

# Joining of Long Reaction-Bonded SiC Tubes

- hermetic joint;
- joint strength comparable to as-rec'd material

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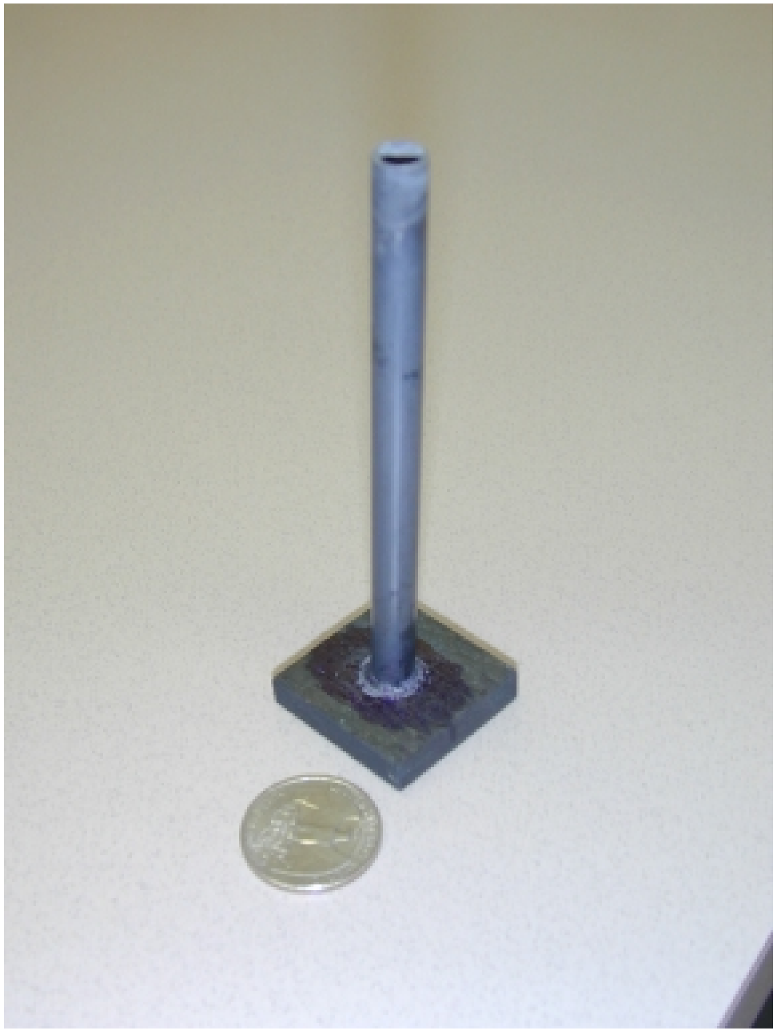
# Joining of Sintered SiC Tube to $SiC_f/SiC_m$ Composite Plate



Achieved static bending moment > 39 in-lb

☞ exceeded the specification of 24 in-lb

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# Joining of Dissimilar Materials

*Sintered SiC to superalloy*

*Induction-joined sapphire-to-stainless steel*

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# Fact Sheet 1 – Hermeticity Tests of Joined SiC Tubes

| Specimen Identification# | Vacuum pressure inside the joined SiC tubes ($10^{-3}$ Torr) | | | |
|---|---|---|---|---|
| | First infiltration | 2nd infiltration | 3rd infiltration | 4th infiltration |
| 021205 | 390 | >500 | | |
| 021217 | 25 | | | |
| 030103 | 450 | | | |
| 030330 | 170 | 75 | <1 | |
| 030430 | 85 | 20 | | |

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# Fact Sheet 2 – Tensile Test Results of RB SiC Tubes

| Specimen Identification | Tube OD x ID (in) | Tube thickness (in) | Max. load (lb) | Tensile strength (MPa) |
|---|---|---|---|---|
| As-rec'd SiC tube | 2-3/8" x 2-1/8" | 1/8" | 4750 | 39.2 |
| 21202 | | | 2300 | 19.0 |
| 30105 | | | 4850 | 40.0 |
| 30331 | | | 4650 | 38.4 |

Joined units showed similar mechanical strength as as-rec'd material.
Specimen 21202 was heated beyond RB SiC's operating range.

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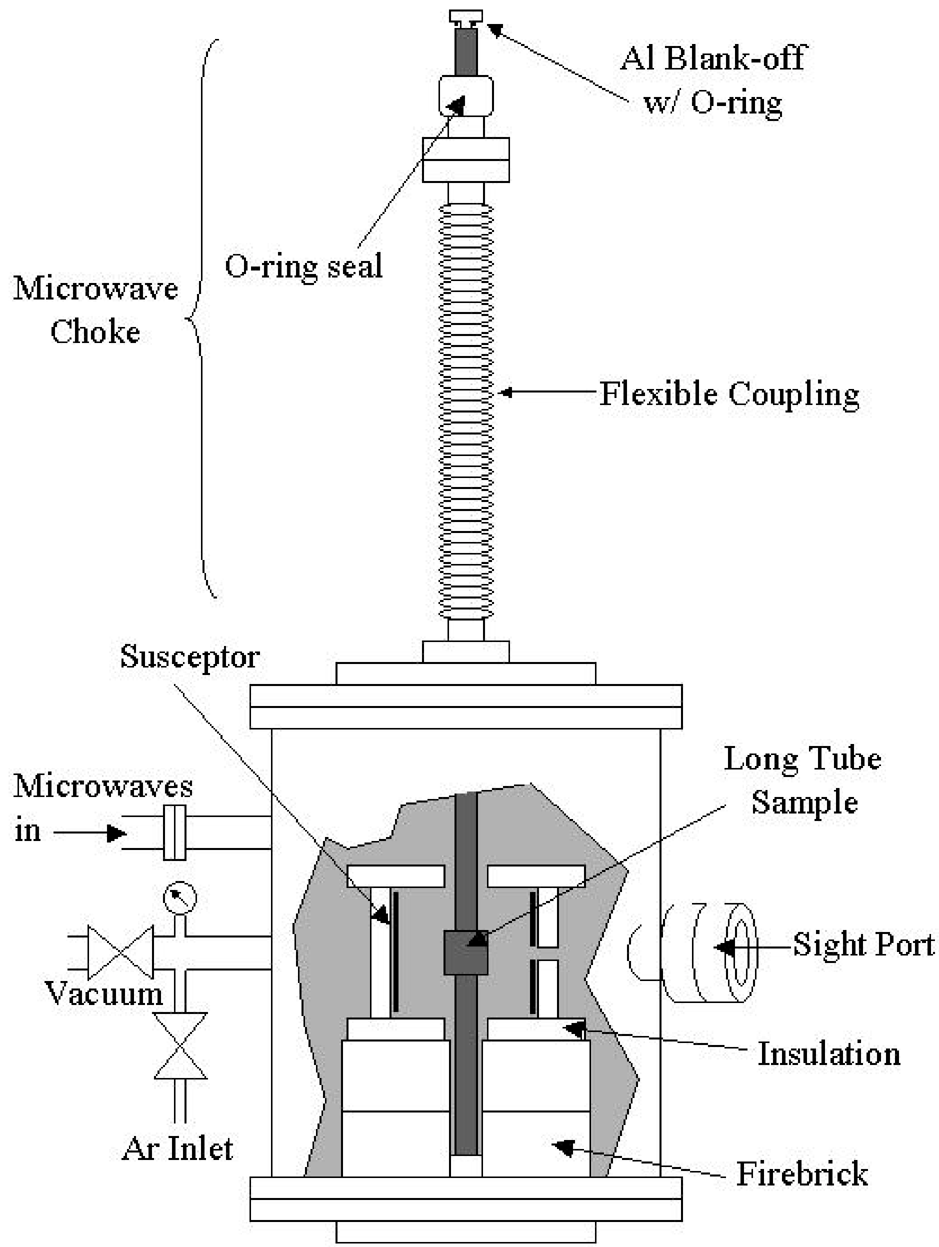
# FMT's Joining Scheme for SiC Components

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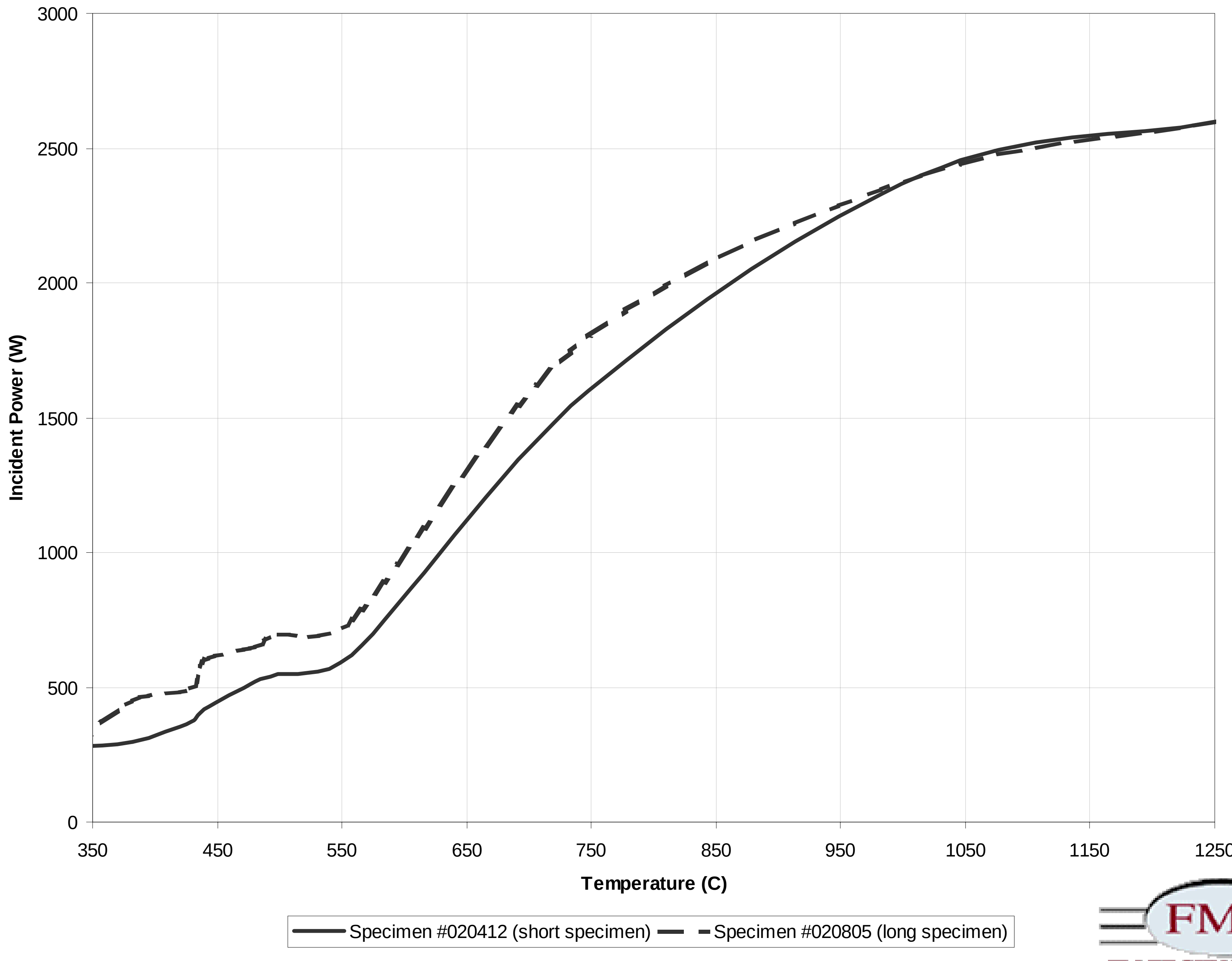
# Microwave Power versus Temperature for different Tube Size

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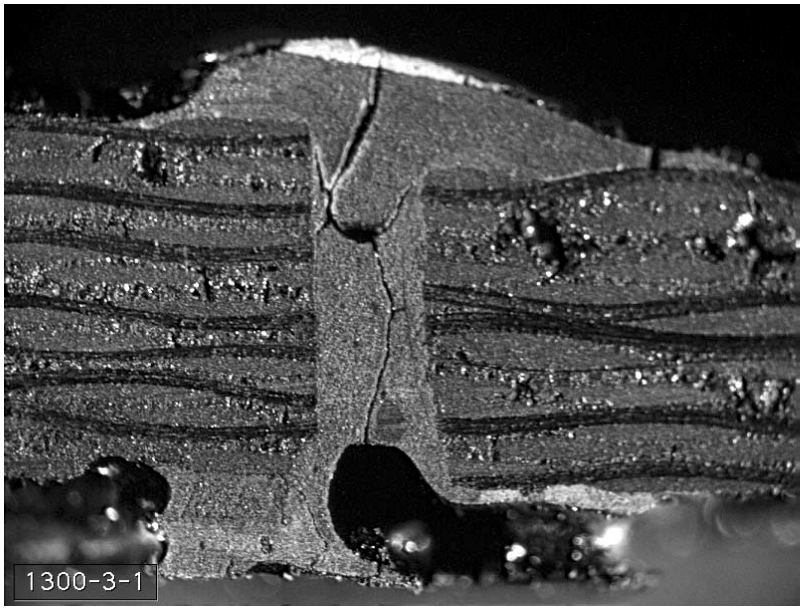
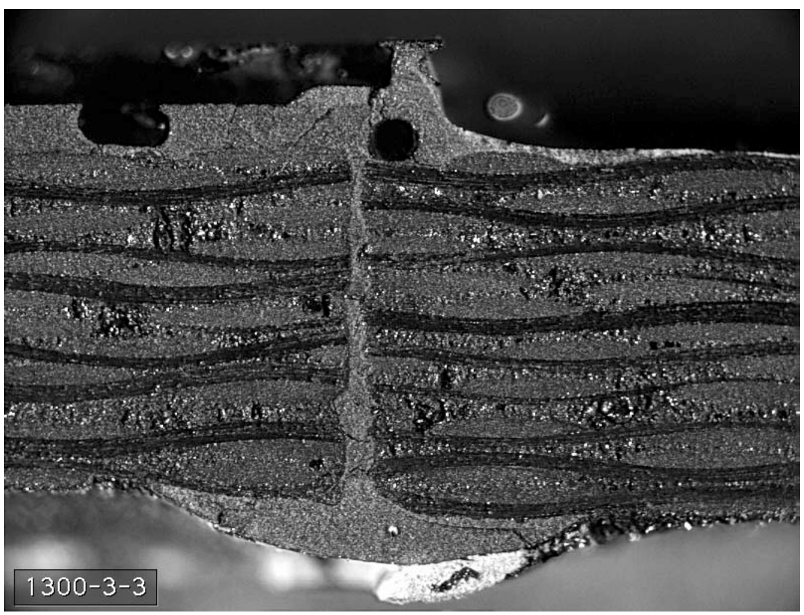
# Previous Preliminary Experiments on $SiC_f/SiC_m$ Composite Joints

## -- Prelude to the Current R&D

1300°C Plate 3








1300-3-1 (@RT) strength = 91.45 MPa
1300-3-2 (@RT) strength = 106.84 MPa
1300-3-3 (@1100°C) strength = 142.09 MPa

Strength depends on quality of joint – thickness, imperfections

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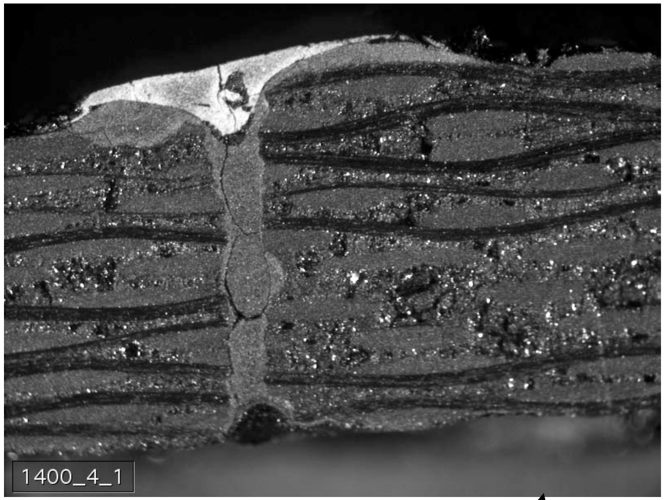
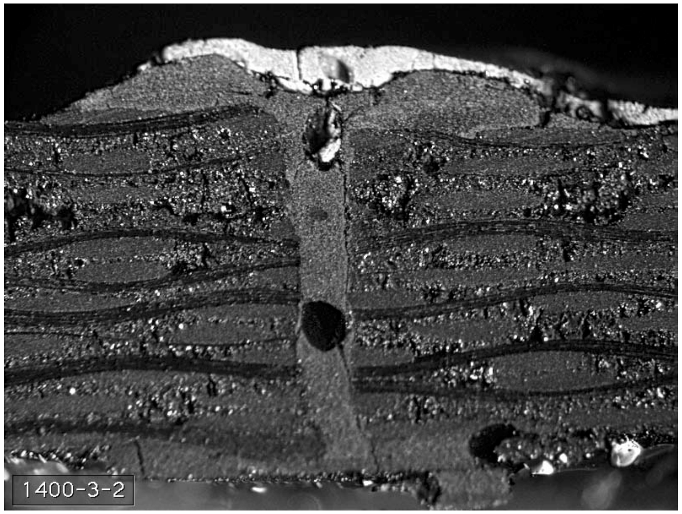
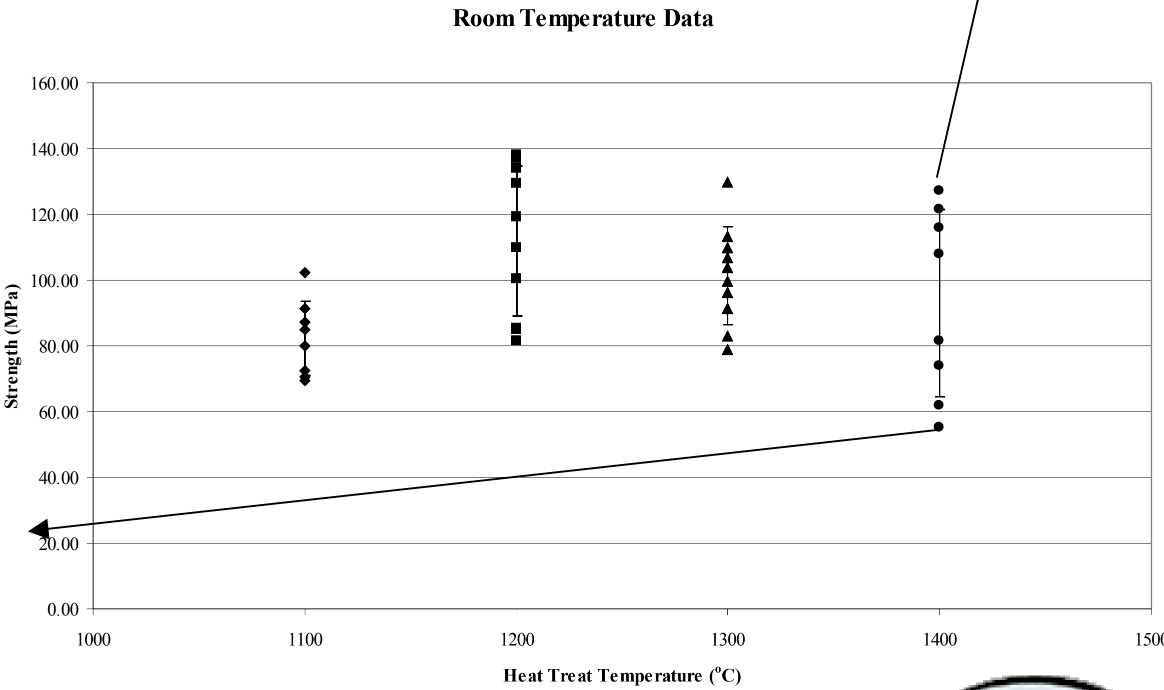
# Explanation of Outlier Data and Spread

Porosity in joint greatly degrades the strength.

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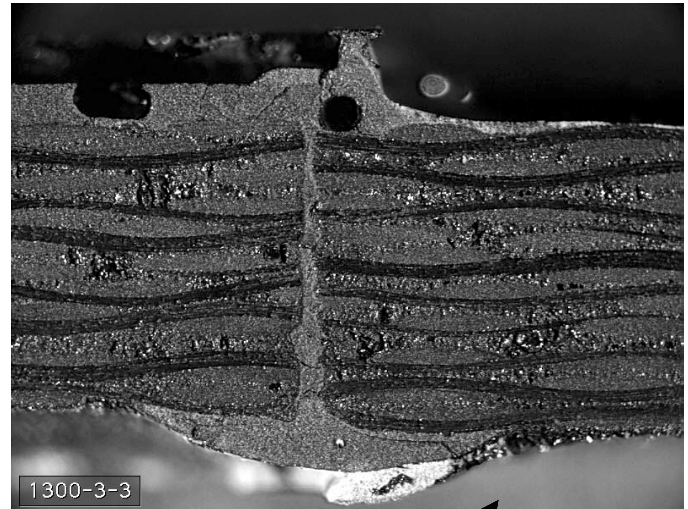
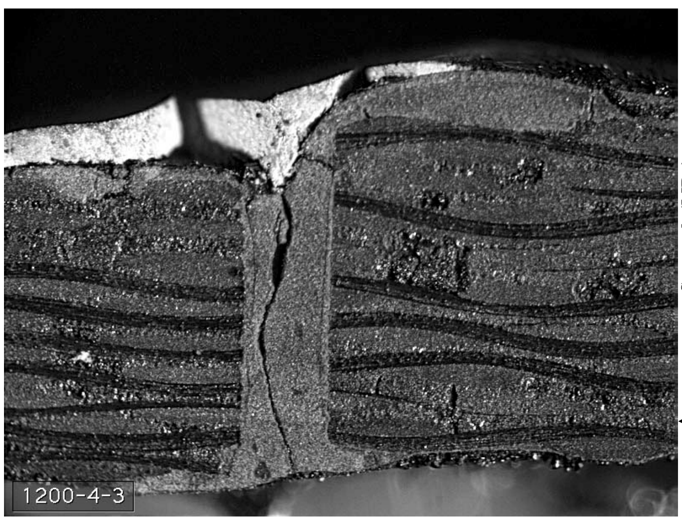
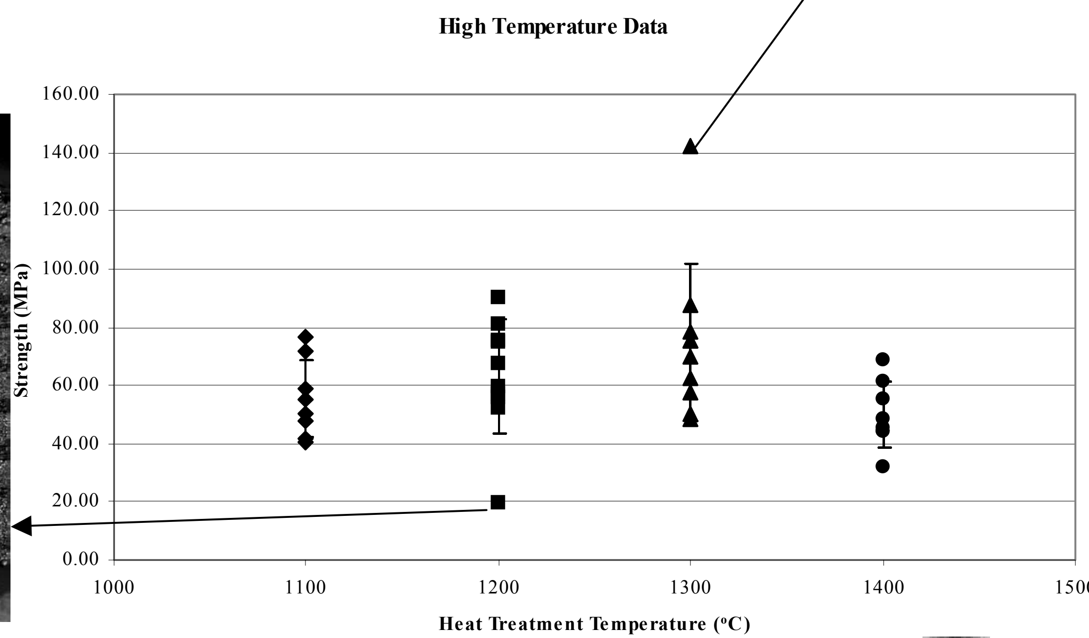



Thickness of joint and cracks in joint both degrade the overall strength.

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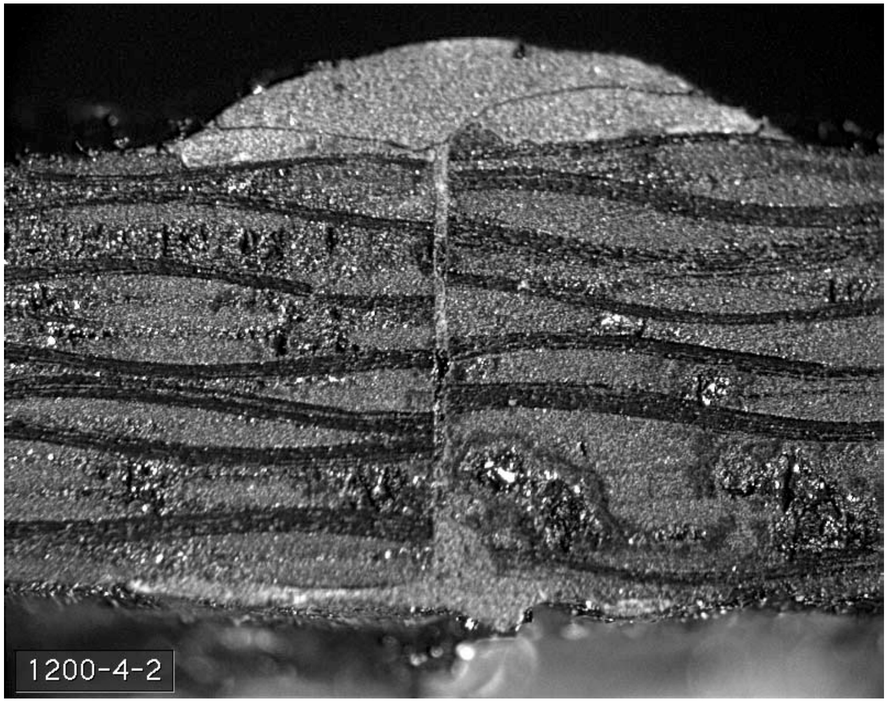
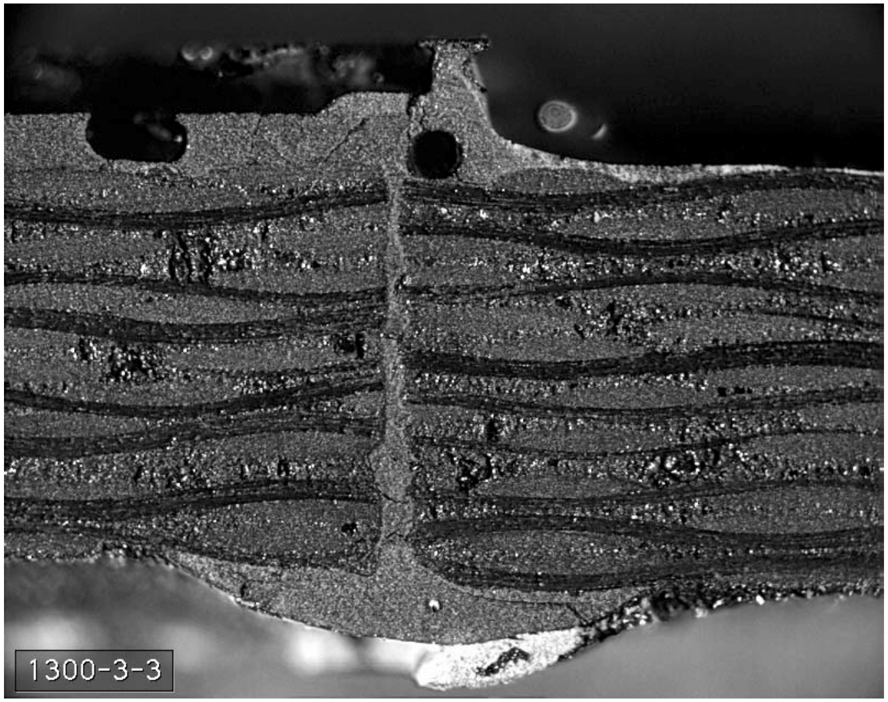
# The strongest samples at both room temperature and high temperature displayed very thin, low porosity joints

1200-4-2 (tested at room temperature)
Strength = 137.96 MPa




1300-3-3 (tested at 1100$^{o}$C)
Strength = 142.09 MPa

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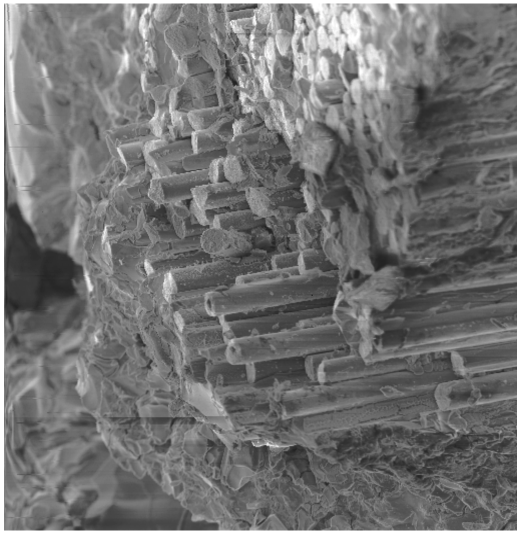
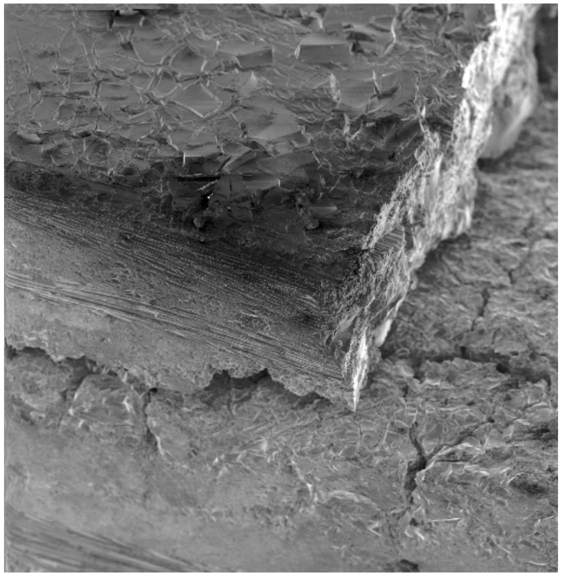
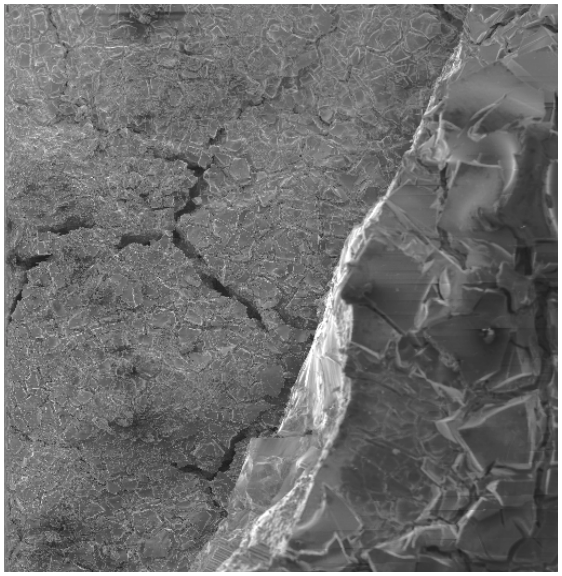
# SEM Picture of a Joint Site

Delamination failure







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# Major Highlights of Current SBIR Efforts on Joining – $SiC_f/SiC_m$ and $C_f/SiC_m$

Thrust areas of current R&D:

• determining the optimum joining geometry -- modeling and experiments

• rapid processing scheme for joining -- cost/performance tradeoff

• evaluation of mechanical strength, examination of microstructures, evaluation of the size/shape/composition of acceptable flaws in joints

• connection of the above parameters to the desired thermo-mechanical characteristics of joints, especially for fusion-relevant environments, for example, thermal load and neutron flux.

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## Estimated range of flaw size, c, for a set of failure stress $\sigma_f$ (first column) and fracture toughness $K_{1c}$ (first row)

$$c = \frac{\gamma^2 K_{IC}^2}{\sigma_f^2}$$

| Failure Stress $\sigma_f$ (MPa)/Fracture toughness $K_{IC}$ (MPa-$\sqrt{m}$) | 2.0 | 2.5 | 3.0 |
|---|---|---|---|
| 100 | 125-202 | 195-316 | 201-454 |
| 200 | 56-90 | 88-141 | 126-202 |
| 300 | 31-50 | 48-78 | 70-112 |

Flaw size of 100 micron or smaller will not significantly perturb achieving a mechanical strength of ~200 MPa.

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## Critical Issues Identified

- Small joint thickness desirable; criticality of alignment of the joining faces; joining geometry

  ☞Modeling and experiments

- Appropriate processing of joining material
- Good mixing of the FMT-proprietary mixture with polymer to provide uniform distribution of the filler material

  ☞ Optical microscopy and SEM of the joined surface

- Crystallinity of the joining material and its uniform characteristics over the joining surface

  ☞XRD studies of the joined surface

  ☞☞☞ Rapid processing (3 infiltrations)

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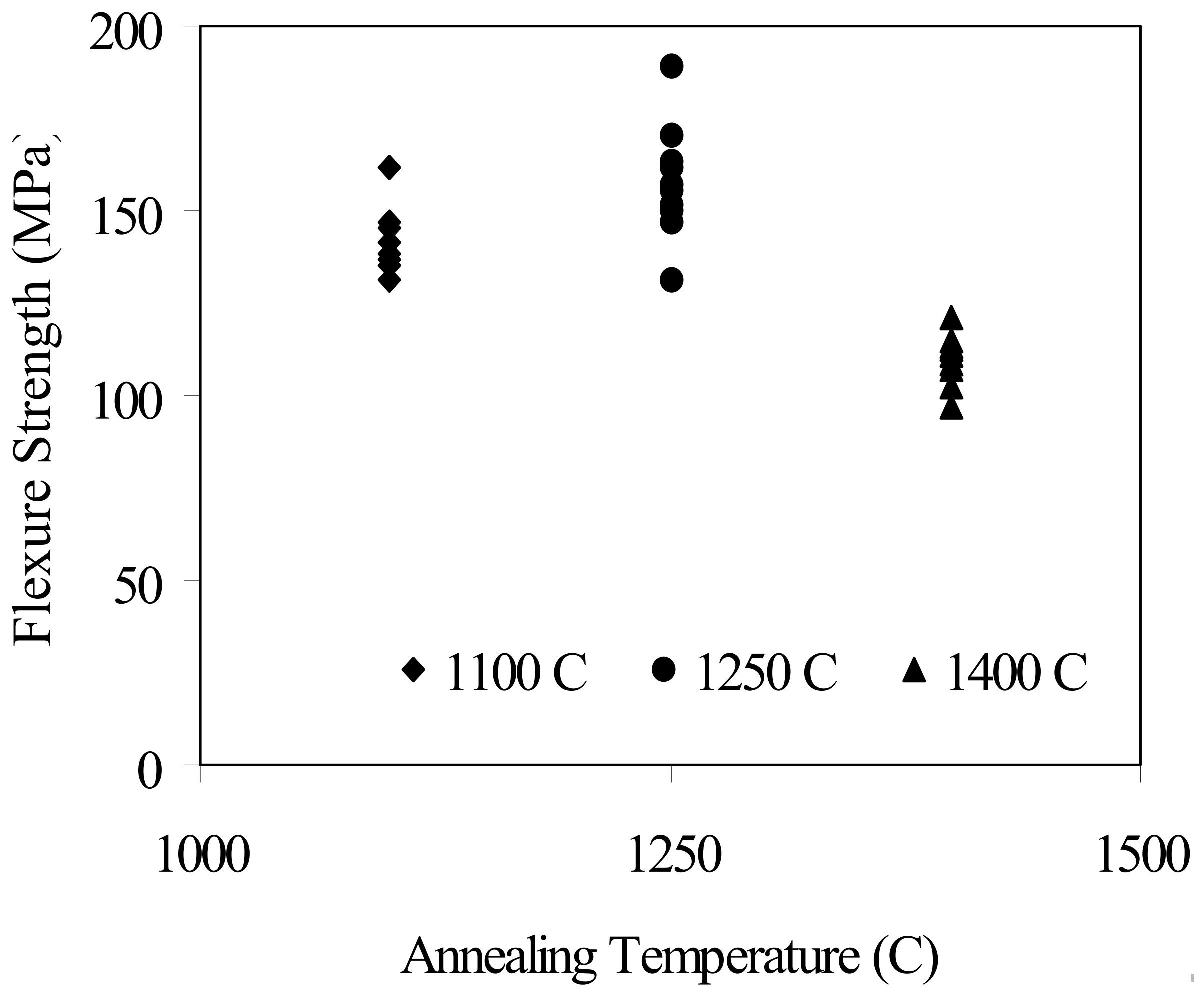
# Flexure Strength vs. Annealing Temperature of Joined $SiC_f/SiC_m$ Composites

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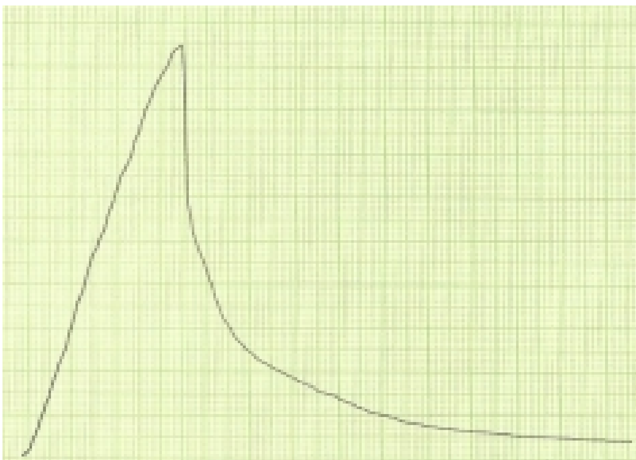
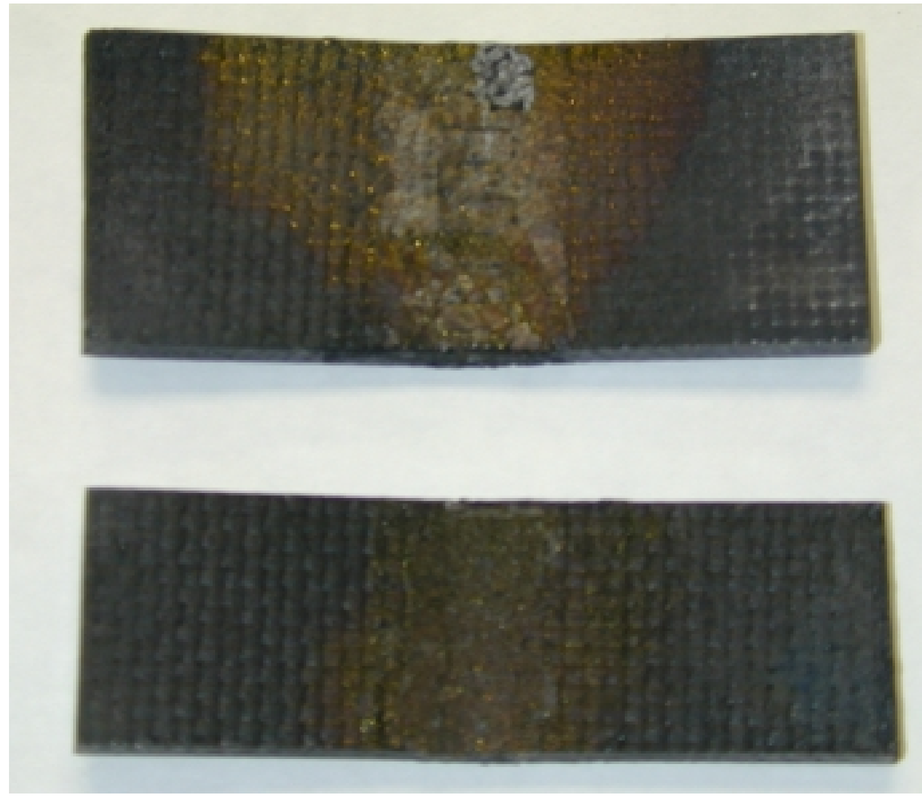
# Photograph of Joined Samples after Flexure Tests



L
o
a
d

Crosshead
displacement



**Typical load (stress) vs. displacement (strain) plot in 4-point flexure tests. This case corresponds to a 20 mm wide sample; the peak load was 189 lb. Load: 20 lb per 10 minor division (vertical); displacement: 0.005” per 10 minor division (horizontal).**

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# Major Accomplishments in Phase I and Phase II Roadmap

- Determined optimum joining geometry ☞ modeling and experiments;
- Developed processing scenario to achieve systematically good results (high mechanical strength)

  ☞ cost/performance tradeoff;
- Flaws, microstructures and crystallinity of joining material studied --- optical microscopy, SEM, XRD
- Processing speed significantly improved – three infiltrations required

  ☞ critical role of pre-processing of joining material;
- Flexure strength of 160±15 MPa achieved for joined $SiC_f/SiC_m$ samples annealed at 1250°C (~55-60% of as-received material); ~108±6 MPa for $C_f/SiC_m$ in very preliminary experiments

  ☞ strength depends on annealing temperature;
- Phase II plan – (a) statistics of joints' performance for the optimized geometry, (b) evaluation of thermal characteristics (thermal conductivity, thermal stress) – reliability roadmap for desirable thermo-mechanical properties of joined parts, (c) build a proto-type processing unit for in-field fabrication/repair.

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