Robust Joining and Integration of Advanced Ceramics and Composites: Challenges, Opportunities, and Realities

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Abstract

Advanced ceramics and fiber reinforced composites are under active consideration for use in a wide variety of high temperature applications within the aeronautics, space transportation, energy, and nuclear industries. The engineering designs of ceramic and composite components require fabrication and manufacturing of large and complex shaped parts of various thicknesses. In many instances, it is more economical to build up complex shapes by joining simple geometrical shapes. In addition, these components have to be joined or assembled with metallic sub-components. Thus, joining and attachment have been recognized as enabling technologies for successful utilization of ceramic components in various demanding applications.

In this presentation, various challenges and opportunities in design, fabrication, and testing of high temperature joints in advanced ceramics and ceramic matrix composites will be presented. Silicon carbide based advanced ceramics and fiber reinforced composites in different shapes and sizes, have been joined using an affordable, robust ceramic joining technology. In addition, some examples of metal-ceramic brazing will also be presented. Microstructure and high temperature mechanical properties of joints in silicon carbide ceramics and composites will be reported. Various joint design philosophies and design issues in joining of ceramics and composites will be discussed.

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Challenges, Opportunities, and Realities

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Outline

- Need for Joining and Integration Technologies
- Challenges in Joining of Ceramics and Composites
  - *Joint Design and Testing*
  - *Ceramic- (Ceramic, Metal) system*
  - *Composite- (Composite, Metal) system*
- Ceramic Joining Using ARCJoinT
  - Monolithic Silicon Carbide Ceramics
  - Composites (SiC, C/SiC, C/C)
- Bonding of Ceramics and Composites to Metals
  - *Titanium to C/C composites*
- Applications
- Summary and Conclusions

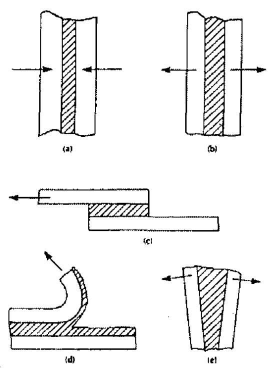
Need for Joining and Integration Technologies

- **Joining and integration technologies are key to development and utilization of advanced ceramics and composites in aerospace and ground based applications.**
  - **Aerospace Systems**
    - ***Aerospace and Space Propulsion Components (Combustor Liners, Exhaust Nozzles, Nozzle Ramps, Turbopump Blisks)***
    - ***Thermal management systems (Radiators, recuperators), optical components, and dimensionally stable space structures***
  - **Ground Based Systems**
    - ***Nuclear Industries, Land Based Power Generation, Process Industries, Heat Exchangers, Recuperators, Microelectronic Industries (Diffusion Furniture, Boats)***
- **The development of robust joining and assembly capability will allow the application of advanced ceramics and composites technology in a timely manner.**

Technical and Performance Requirements for Joined Structures

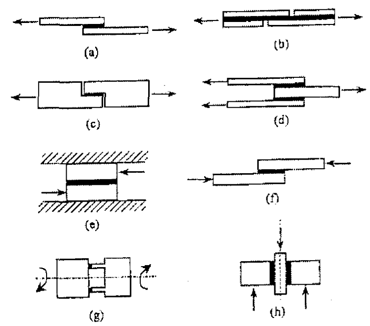
- **Typically for the high temperature aerospace and ground based applications (ceramic and composite- based systems):**
  - Use temperature > 1200 °C *(joint properties comparable to base materials).*
  - Good thermomechanical properties (strength and oxidation resistance)
  - Low CTE mismatch to minimize residual stresses and good thermal shock resistance
  - Leak tight joints
- **In ceramic-metal systems, joint performance is limited by the temperature capability of metallic component in the system (braze/bond layer, metallic substrate). These systems have operational capability around 700-800°C.**
- **Practical, reliable, and affordable technique adaptable to in-field installation, service, and repair.**

Technical Challenges in Design and Selection of Joints in Advanced Ceramics and Composites



(a) Compression; (b) Tension; (c) Shear; (d) Peel; (e) Cleavage

Typical Ceramic Joints will have Combination of Stresses Under Operating Conditions



Different Types of Shear Tests

Technical Challenges in Joining of Ceramic Matrix Composites

- *Joint Design*

- High elastic modulus of ceramic joint materials provides significant challenges to joint design and characterization.

- Understanding of stress state in the joints.

- *Materials Related Issues*

- Optimization of in-plane tensile properties of CMCs by engineering the fiber/matrix interface is accomplished at the expense of interlaminar properties. Weak interfaces complicate joint properties and performance

- Composition and microstructure
- Bonding and adhesion
-Testing and data analysis

- High elastic modulus ceramic joint materials.

- *Life Time Testing for Specific Applications*

- Time dependent thermomechanical properties of joints.
- Environmental effects on joint properties.

Joining of Advanced Ceramics and Composites

- *Monolithic SiC Ceramics*
- *Fiber Reinforced Composites*

Joining of Ceramic Components Using Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Apply Carbonaceous Mixture to Joint Areas
Cure at 110-120°C for 10 to 20 minutes

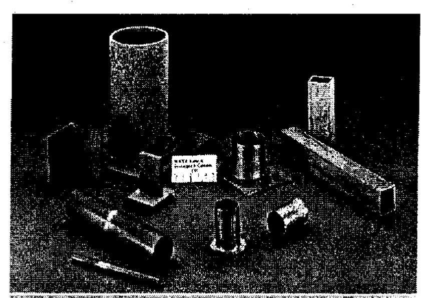
⇩

Apply Silicon or Silicon-Alloy (paste, tape, or slurry)
Heat at 1250-1425°C for 10 to 15 minutes

⇩

Affordable and Robust Ceramic Joints with Tailorable Properties

1999 R&D 100 Award
2000 NorTech Innovation Award



Advantages
- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

ARCJoinT is Currently Being Used to Join and Repair a Wide Variety of Ceramic and Composite Materials

SiC-Based Ceramics
- Reaction Bonded SiC
- Sintered SiC
- CVD SiC, Porous SiC

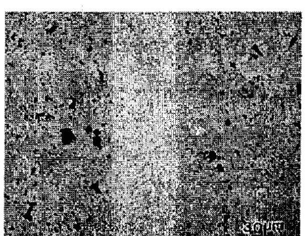
SiC/SiC Composites
- Melt Infiltrated SiC/SiC
- CVI SiC/SiC Composites
- PIP SiC/SiC Composites

C/SiC Composites
- Melt Infiltrated C/SiC
- CVI C/SiC Composites
- PIP C/SiC Composites

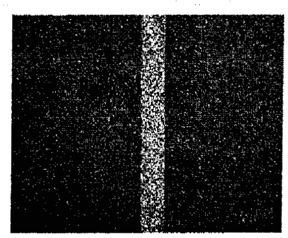
C/C Composites
- CVI C/C Composites
- Resin Derived C/C
- C-C/SiC with MI

- ***Composites with Different Fiber Architectures and Shapes***
- ***Ceramics with Different Shapes and Sizes***

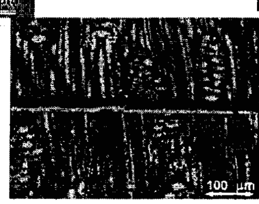
Microstructure of As-Fabricated Joints in Monolithic SiC Ceramics

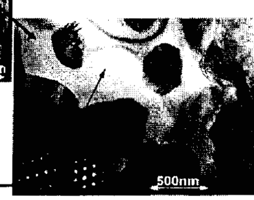


Sintered SiC (Hexoloy-SA)



CVD-SiC

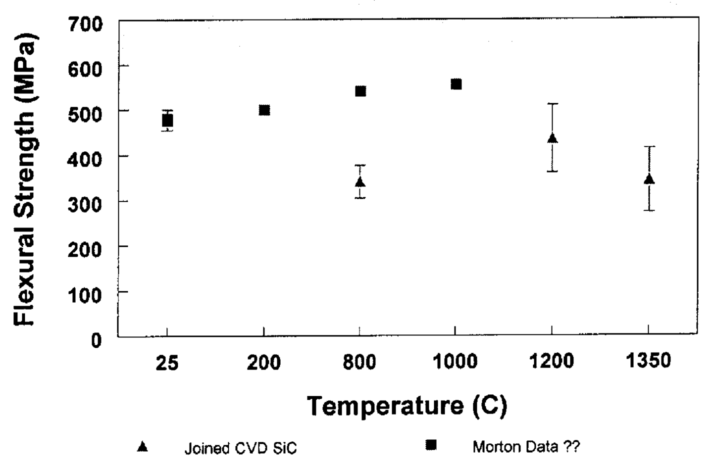




Ecoceramics

African Bubinga

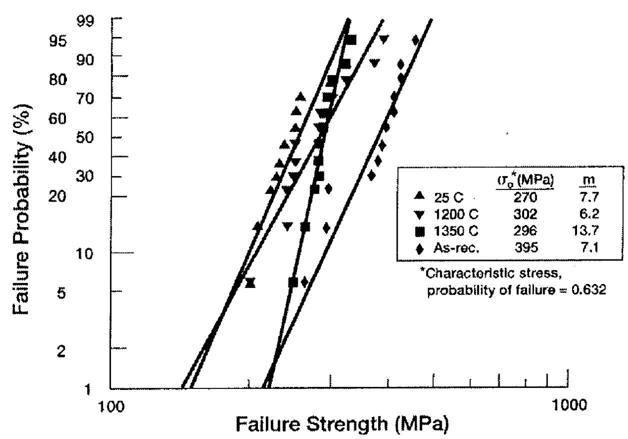
Flexural Strengths of Joined CVD SiC Ceramics



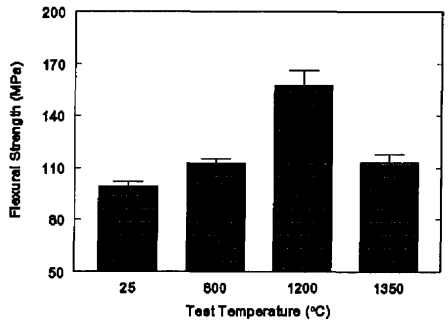
Average data for five specimens

No. of specimens unknown

Fracture Strength Distribution of Joined SiC (Hexoloy-SA) at Different Temperatures



Microstructure and Mechanical Properties of Joined MI Hi-Nicalon/BN/SiC Composites

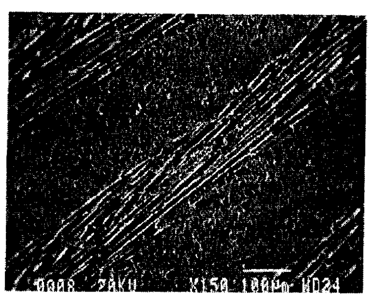


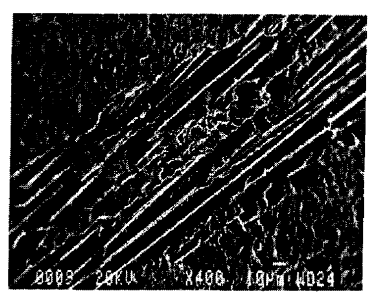
Flexural Strength of Joined SiC/SiC Composites

MI SiC/SiC Composite

Joint-Composite Interface

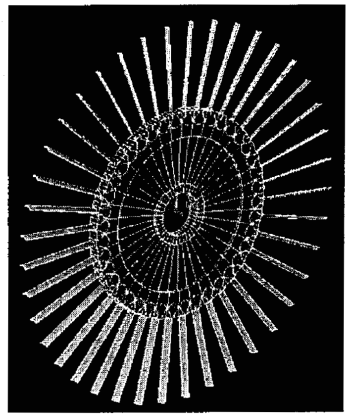
SEM Micrographs of Joints in MI SiC/SiC Composites Tested at 1200°C

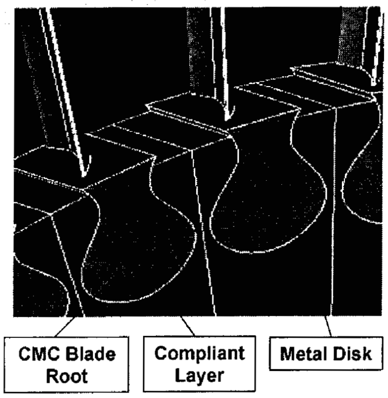




BN coated interfaces acted as a weak link at the joint interface due to their low interfacial shear strengths

Fabrication of Thick C/SiC and SiC/SiC CMC Subelements



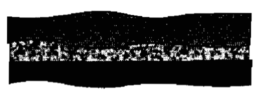


Need for a joining and attachment technology that both accommodates the material differences between the CMC blade and the metallic disk and matches the operational thermal-mechanical loads to the CMC material capabilities.

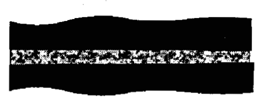
Effect of Surface Roughness on the Shear Strength of Joined CVI C/SiC Composites

CVI C/SiC Composites

Joints with As-Fabricated Surfaces



Joints with As-Fabricated/ Machined Surfaces

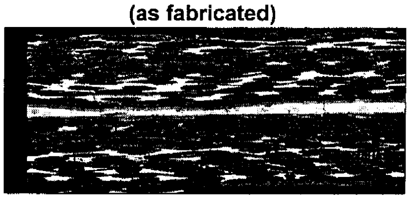


Joints with Machined Surfaces

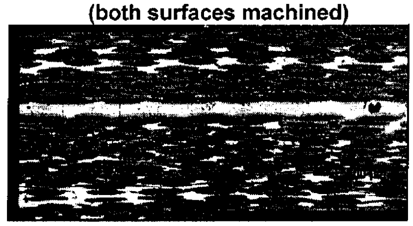
Microstructure of As-Fabricated and Joined CVI C/SiC Composites

CVI C/SiC Composites
(as fabricated)

Joined CVI C/SiC Composites
(both surfaces machined)

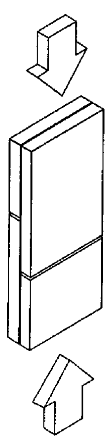


Joined CVI C/SiC Composites
(one surface machined and
one surfaces as received)



Joined CVI C/SiC Composites
(both surfaces as received)

Specimen Geometry and Test Fixture Used for Compression Double-Notched Shear Tests



ASTM C 1292-95a (RT) and ASTM C 1425-99 (HT)

Specimen Dimensions

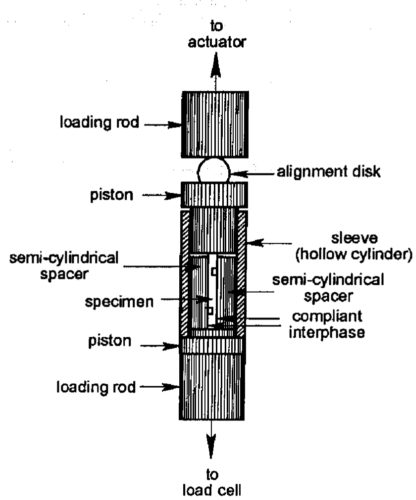
Specimen length (L) : 30 mm *(±0.10 mm)*

Distance between notches (h) : 6 mm *(±0.10 mm)*

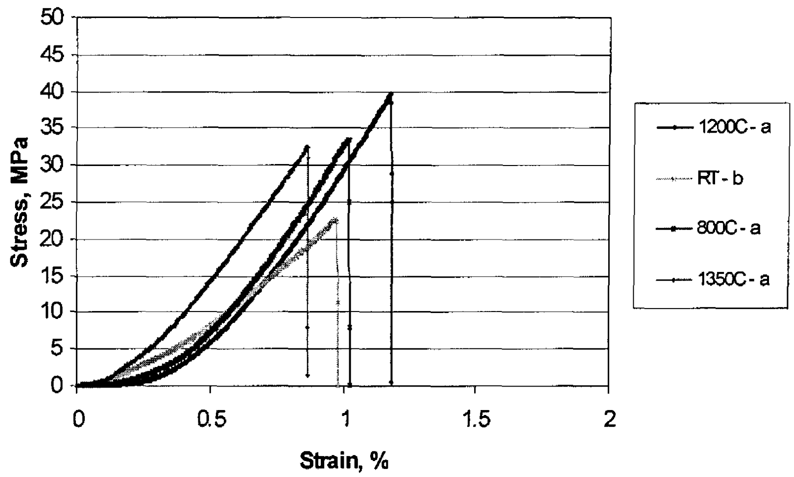
Specimen width (W) : 15 mm *(±0.10 mm)*

Notch width (d) : 0.50 mm *(±0.05 mm)*

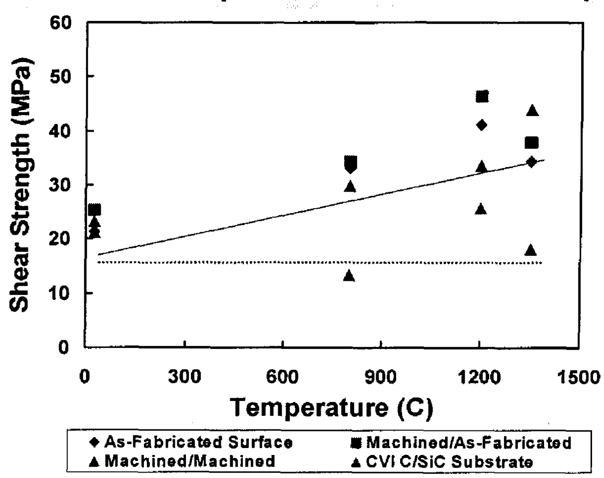
Specimen thickness (t) : *(adjustable)*



Typical Stress-Strain Behavior Obtained During the Compression Double-Notched Shear Tests



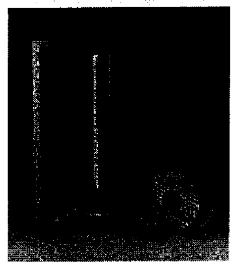
Compression Double Notch Shear Strength of Joined CVI SiC Composites at Different Temperatures



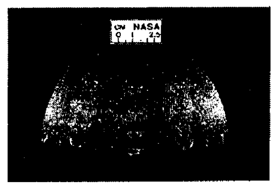
- Shear strength of joints increases with temperature and is higher than the CVI SiC composite substrate.
- No apparent influence of surface condition on the shear strength of joints.

Examples of Components Joined Using ARCJoinT

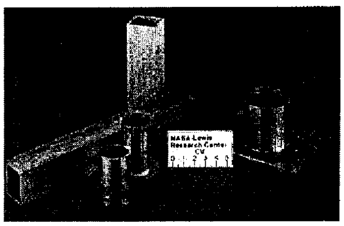
SiC Tubes for Wafer Fabrication System



Cabon-Carbon Composite Valves for Race Car Engines



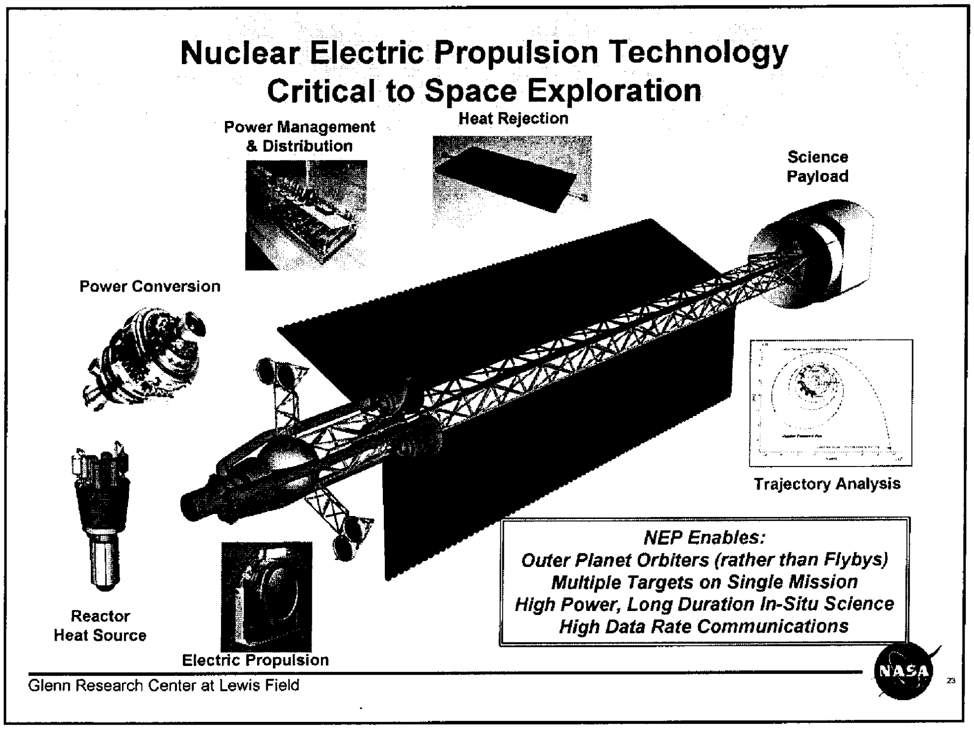
Attachment for Sensors



Joined C/SiC Composites

Bonding of Ceramics and Composites to Metals

- Titanium to C/C composites


Nuclear Electric Propulsion Technology
Critical to Space Exploration
Power Management
& Distribution
Heat Rejection
Science
Payload
Power Conversion
Trajectory Analysis
NEP Enables:
Outer Planet Orbiters (rather than Flybys)
Multiple Targets on Single Mission
High Power, Long Duration In-Situ Science
High Data Rate Communications
Reactor
Heat Source
Electric Propulsion
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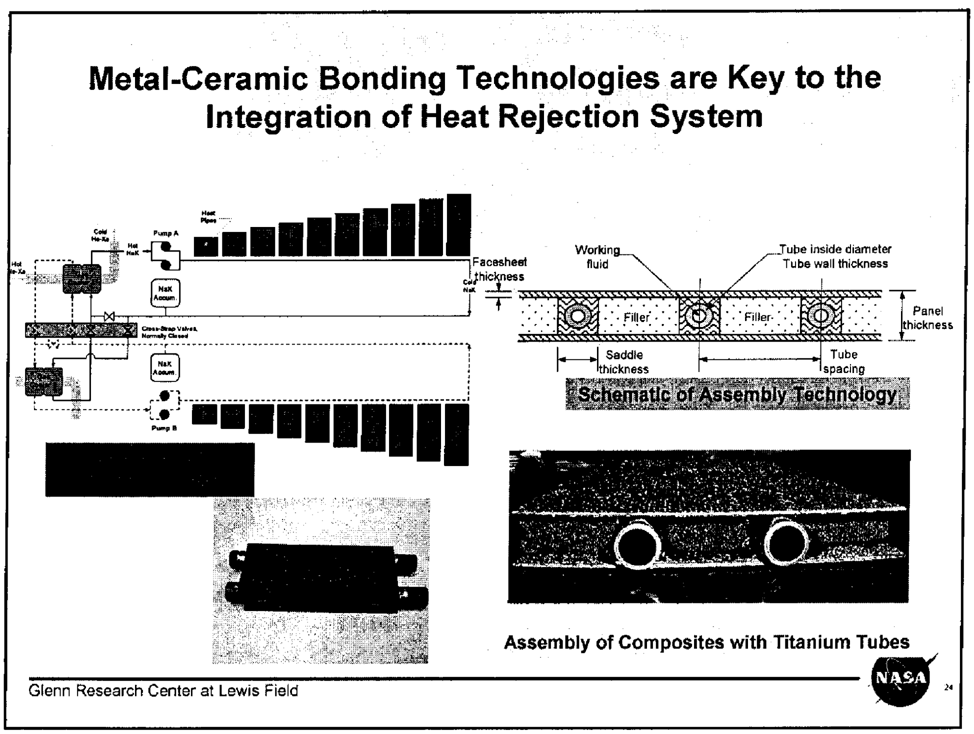
Metal-Ceramic Bonding Technologies are Key to the
Integration of Heat Rejection System
Facesheet
thickness
Working
fluid
Tube inside diameter
Tube wall thickness
Filler
Filler
Panel
thickness
Saddle
thickness
Tube
spacing
Schematic of Assembly Technology
Assembly of Composites with Titanium Tubes
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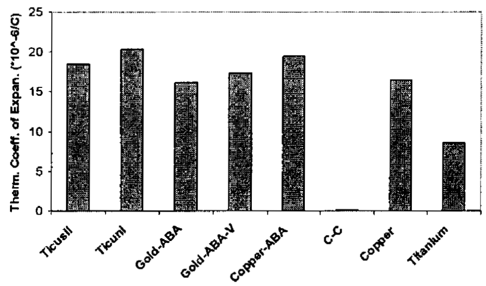
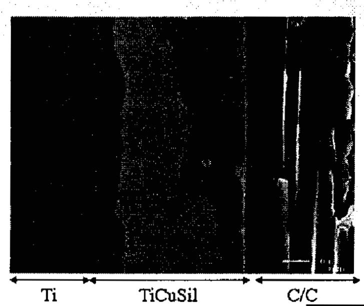
Brazing and Assembly Technologies are Critical for Scale-up and Manufacturing

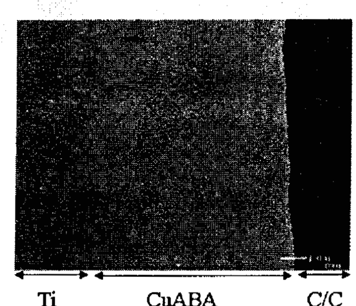
- **Carbon-Carbon composites and metallic components have to be brazed for heat rejection system components.**
- **Due to differences in thermal expansion coefficients of C/C composites and metallic components following issues have to be addressed.**
  - ***Braze composition and compatibility***
  - ***Joint design***
  - ***Mechanical testing and characterization***
  - ***Thermal and environmental durability testing***

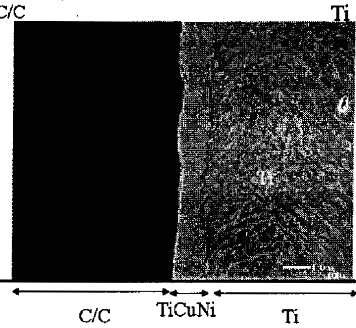


- ***Thermal expansion coefficients of some commercially available brazes, C/C, Titanium, and Copper.***
- ***The chart demonstrates the need for innovative joint design concepts, new braze materials, and robust brazing technology development to avoid deleterious effects of thermal expansion mismatch.***

Good Bonding Between Flat Plates of Braze Compositions to Ti and C-C Composites

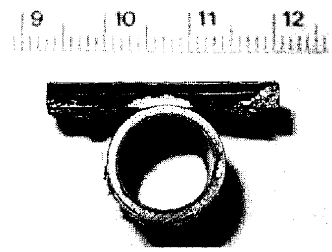


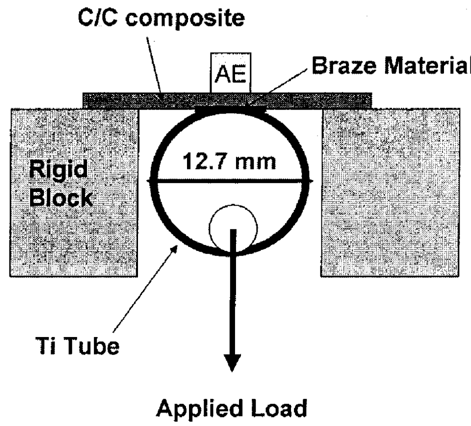




Tube Tensile Test

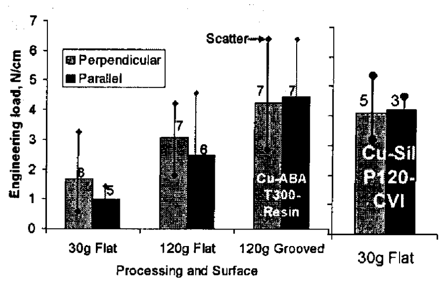
To measure the "tensile strength" of the joint

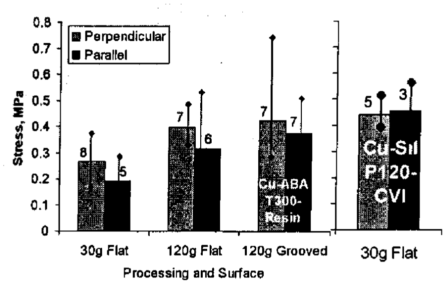


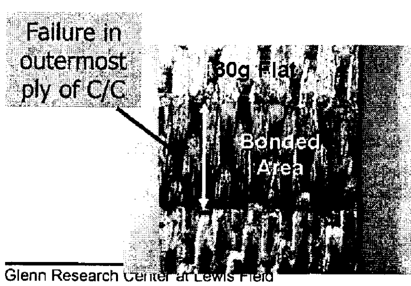


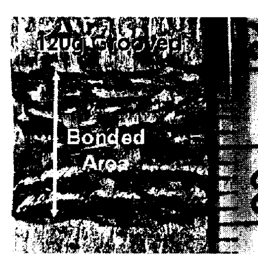
Factors to consider:
- Braze composition
- Processing variables
- Bonded area
- Location of failure
- Architecture effects

Tube Tensile Test Results: Effect of Processing Load, Curvature, and Matrix Processing









Summary and Conclusions

- The ARCJoinT process has been used to make several types of joints in SiC, C/SiC, and SiC/SiC composites. Joints in monolithic ceramics (CVD and Sintered SiC) show ~75% of the strength compared to bulk materials.
- In C/SiC composites, whether the joined surfaces are as-received (rough) or machined (smooth) has no effect on the shear strength of the joint. Furthermore, the shear strength of all joints exceeds that of the as-received C/SiC at elevated temperatures up to 1350 C.
- High elastic modulus of ceramic joints and weak interfaces in composite materials provide significant challenges to joint design and are critical to joint properties and performance.
- Thermal expansion mismatch between C-C/braze/Titanium and interlaminar properties of C/C composites play a key role in mechanical behavior of joint.
- A combination of tensile, shear, and flexural testing of joints coupled with fracture mechanics based design and analysis is needed to generate useful engineering design data.
- Time dependent high temperature thermomechanical properties are critical for the successful utilization of ceramic joining technology for advanced ceramics and fiber reinforced composite materials.