Robust Joining and Assembly Technologies for Ceramic Matrix Composites: Technical Challenges and Opportunities

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Abstract

Fiber reinforced ceramic matrix composites are under active consideration for use in a wide variety of high temperature applications within the aeronautics, energy, process, and nuclear industries. The engineering designs require fabrication and manufacturing of complex shaped parts. In many instances, it is more economical to build up complex shapes by joining simple geometrical shapes. 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 ceramic matrix composites will be presented. Various joint design philosophies and design issues in joining of composites will be discussed along with an affordable, robust ceramic joining technology (ARCJoinT). A wide variety of ceramic composites, in different shapes and sizes, have been joined using this technology. Microstructure and mechanical properties of joints will be reported. Current status of various ceramic joining technologies and future prospects for their applications will also be discussed.

Robust Joining and Attachment Technologies for Ceramic Matrix Composites:

Technical Challenges and Opportunities

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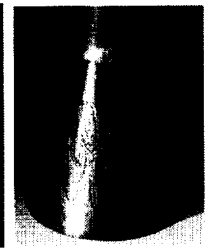
Outline

- Background and Rationale
- Technical Challenges
  - *Joint Design and Fabrication*
  - *Testing Methodology*
  - *Environmental Durability of Joints*
  - *Life Prediction of Joined Components*
- ARCJoinT Technology
- Results and Discussion
  - *C/SiC Composites*
  - *SiC/SiC Composites*
  - *Attachments for Sensors*
- Opportunities
- Summary and Conclusions

Joining and Assembly Technologies Through the Ages

Prehistoric Civilization
Attachment Technology for Hunting Tools



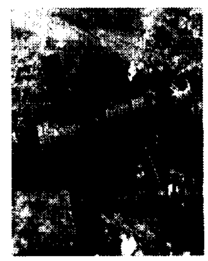
Bronze Age *(7000-1000 BC)*
Brazing and Soldering Used for Jewelry and Domestic Articles

Shang Dynasty
Ceremonial Vessel ~ 1100 BC

Eiffel Tower, Paris
1889

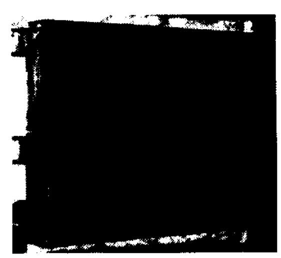
Microelectronics Packaging

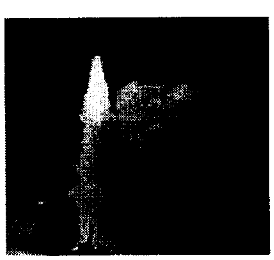
Aerospace and Defense

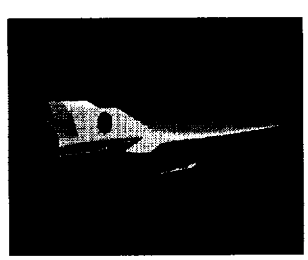


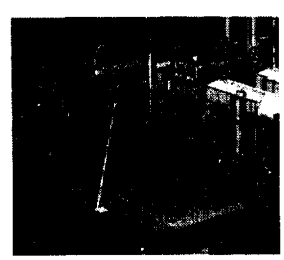
International Space Station

Ceramic Matrix Composites are Enabling Materials for Numerous Aerospace and Ground Based Systems

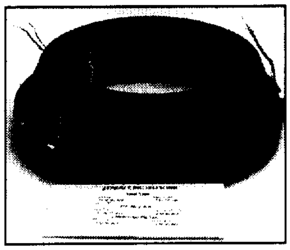


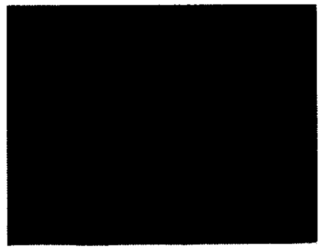


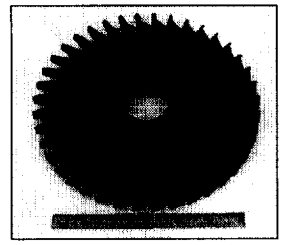


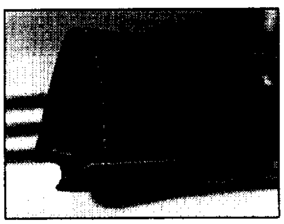


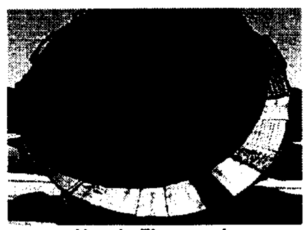
Ceramic Matrix Composites Components for Aerospace and Ground Based Systems


Combustor Liner


Turbopump Stator


Turbine Rotor


Turbine Rear Frame Leading Edge


Nozzle Flaps and Seals


Interstage Shroud

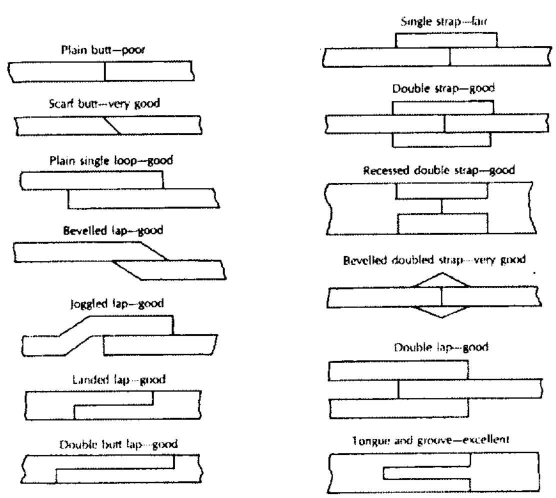
Need for Joining and Attachment Technology

- **Joining is an enabling technology for utilization of advanced ceramics and ceramic composites in high temperature applications.**
  - **Aerospace Systems**
    - ***Aerospace and Space Propulsion Components (Combustor Liners, Exhaust Nozzles, Nozzle Ramps, Turbopump Blisks)***
  - **Non-Aerospace Systems**
    - ***Nuclear Industries, Land Based Power Generation, Process Industries, Heat Exchangers, Recuperators, Microelectronic Industries (Diffusion Furniture, Boats)***
- **The development of ceramic joining capability will allow the application of advanced ceramics and composites technology in a timely manner.**

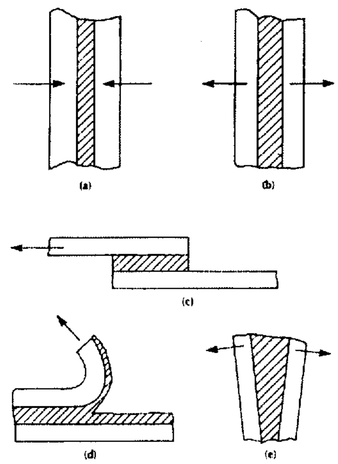
Key Requirements for Joining Technology

- **Joint properties comparable to base materials.**
  - **Use temperature >1200°C**
  - **Good mechanical strength**
  - **Oxidation and corrosion resistance**
  - **Low CTE mismatch to minimize residual stresses**
  - **Good thermal shock resistance**
- **Leak tight joints.**
- **Practical, reliable, and affordable technologies:** ***adaptable to in-field installation, service, and repair.***

Technical Challenges in Design and Selection of Ceramic Joints



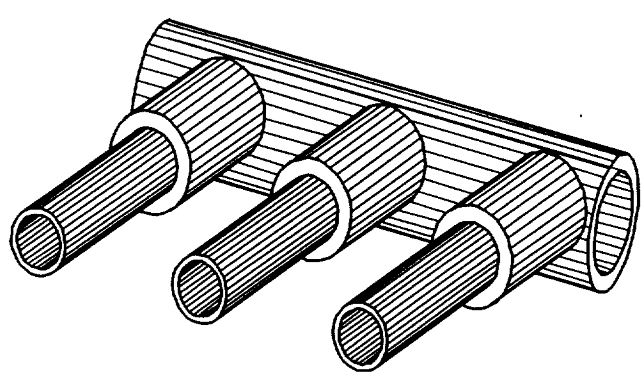
Technical Challenges in Design of Ceramic Joints



Typical Ceramic Joints will have Combination of Stresses Under Operating Conditions

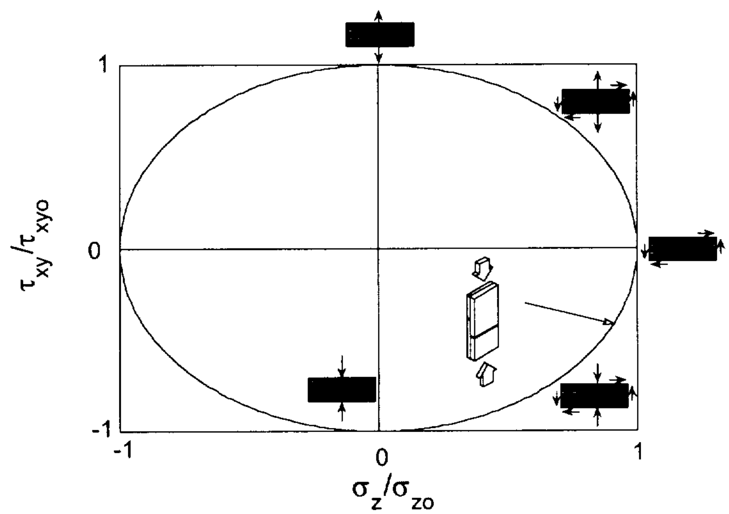
(a) Compression; (b) Tension; (c) Shear; (d) Peel; (e) Cleavage

Schematic of Ceramic Tubes Joined to Ceramic Composite Manifold in a Heat Exchanger



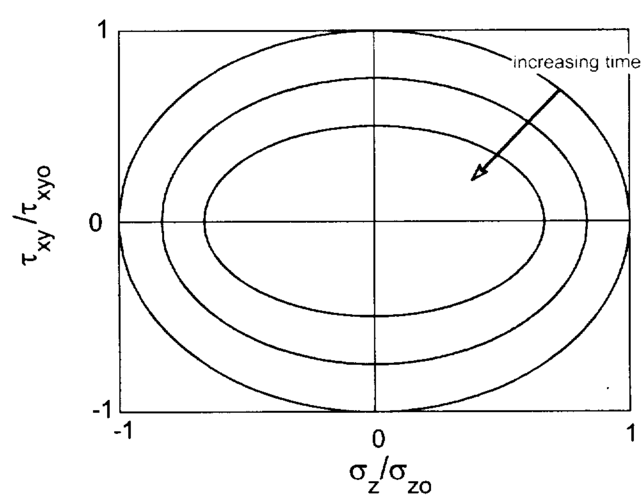
Stresses in the Joint Regions Involve Multiaxial States of Stress
(e.g., Normal Plus Shear Stresses)

Joint Design Map Where Shear and Normal Stresses Have Been Normalized by Virgin Isothermal Joint Strengths

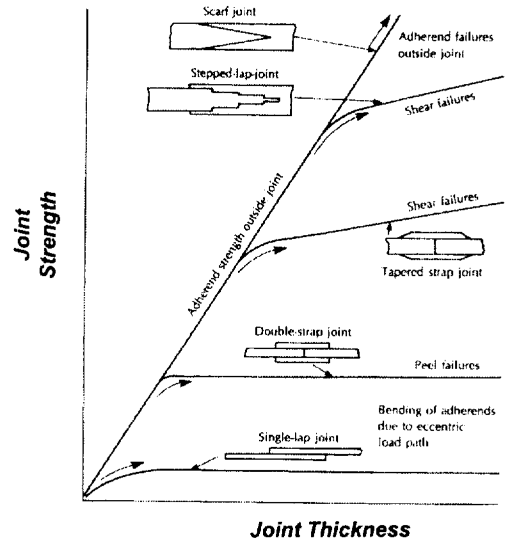


(The Envelope Defines the Strength of the Joint)

Schematic of a Joint Design Map Where the Design Envelope Shrinks due to Degradation of Strength with Time



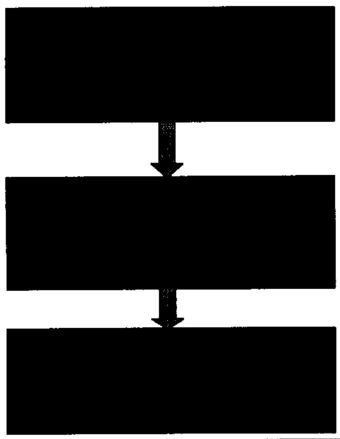
Technical Challenges in Design and Selection of Ceramic Joints

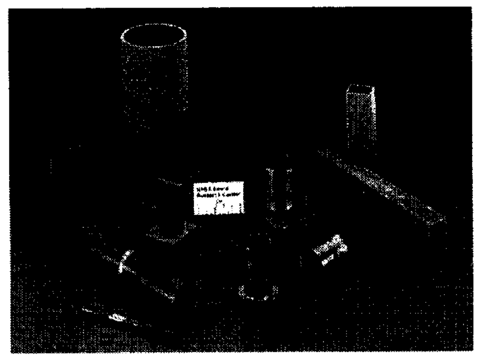


Joining and Attachment Technologies for Ceramics

- **Direct Bonding (Solid-State Joining)**
  - **Fusion Bonding/Welding**
  - **Diffusion Bonding and Friction Welding**
- **Indirect Bonding (Liquid Phase Joining)**
  - **Brazing and Soldering**
  - **Liquid Phase Bonding**
- **Joining with Preceramic Polymers**
- **Reaction Bonding and In-Situ Reactions**
- **Mechanical Attachments**
  - **Threading, Bolting, Clamping, etc.**

Affordable, Robust Ceramic Joining Technology
(ARCJoinT)





1999 R&D 100 Award
2000 EDI Innovation Award

Advantages of ARCJoinT

- 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 Can be 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*

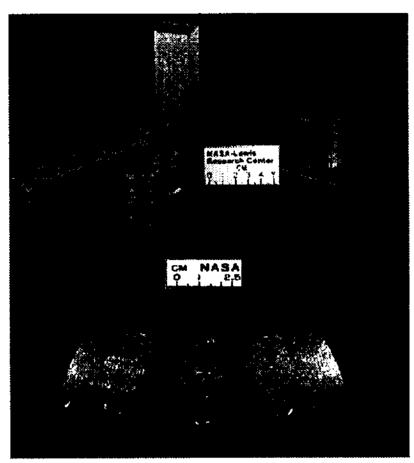
Broad Industrial Applications of Affordable, Robust Ceramic Joining Technology

Aerospace Industry:
- Combustor Liners
- Nozzle Components
- Turbopumps, Thrustors
- Mirrors, Optical Benches, Shielding

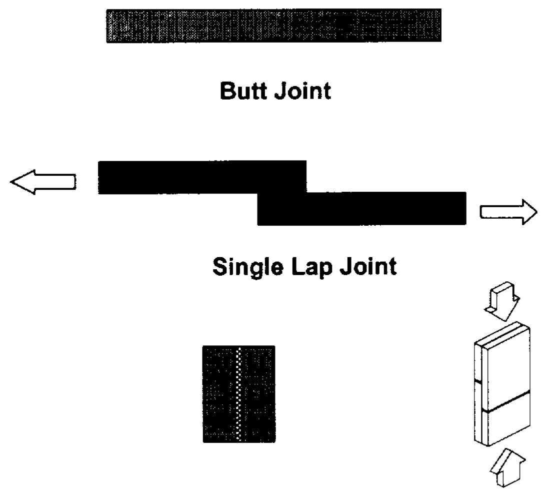
Energy Industry:
- Industrial Heaters, Burners, Filters, Heat Exchangers, Recuperators
- Land-Based Turbine Components

Nuclear Industry:
- Nuclear Reactor Components

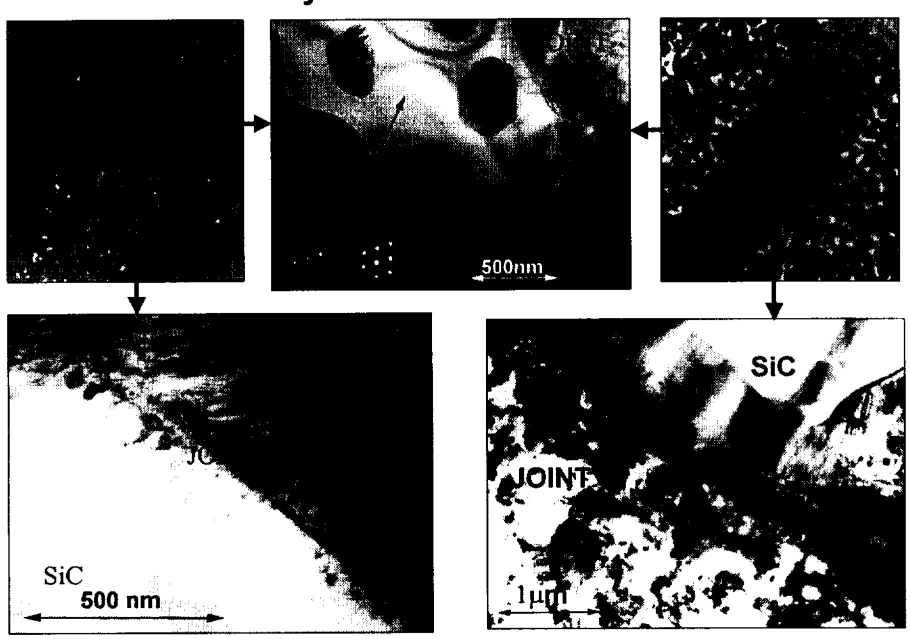
Automotive Industry:
- Valves and Other Components

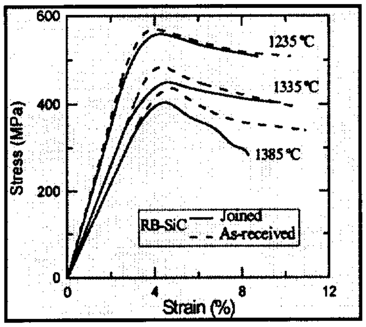


Joint Configurations Used in Present Study



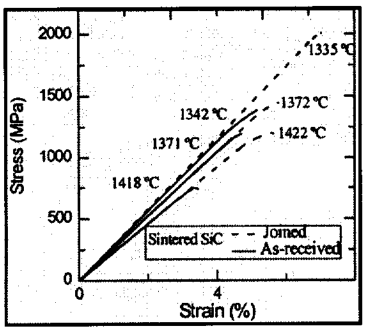
TEM Analysis of Reaction Formed Joints



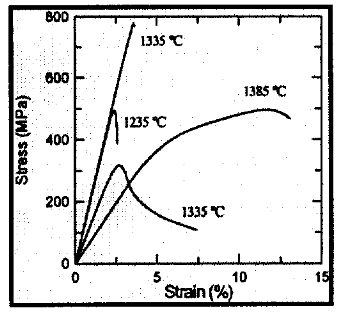


A

Stress vs Strain Behavior as a Function of Temperature

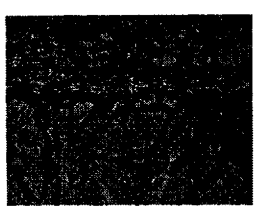


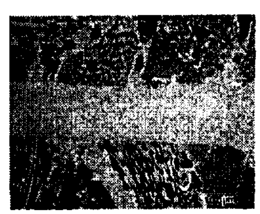
B



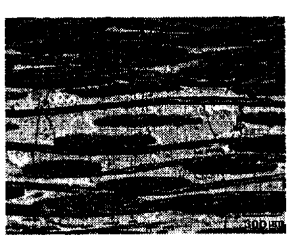
Sintered SiC where a lower pressure than in A) and B) has been used during fabrication

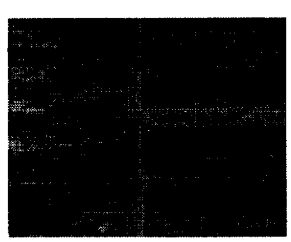
Typical Microstructure of Joined SiC-Based Ceramic Matrix Composites

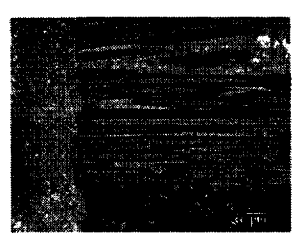




Novoltex® C/SiC Composite Joined Novoltex® Composite





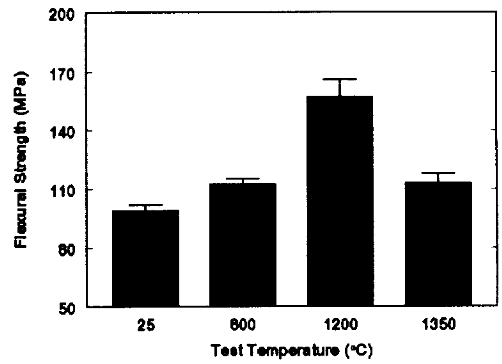


MI C/SiC Composite Joined MI C/SiC Composite Joint-Composite Interface

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

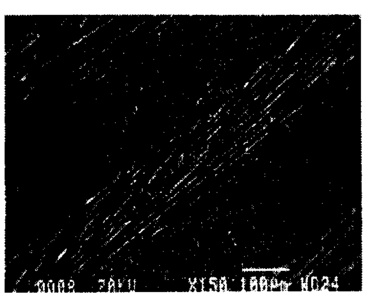
MI SiC/SiC Composite

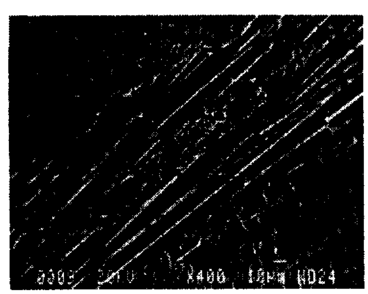
Joint-Composite Interface



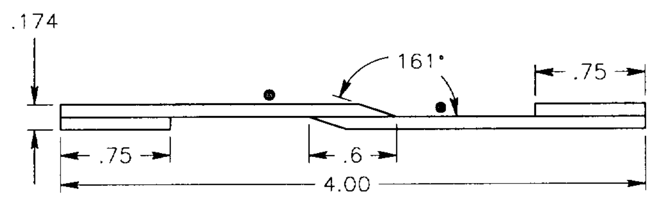
Flexural Strength of Joined SiC/SiC Composites

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

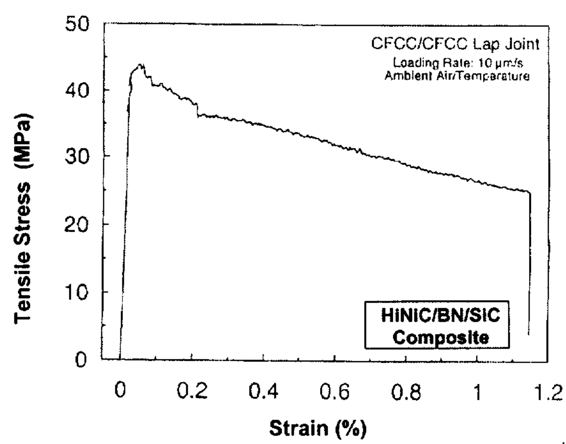




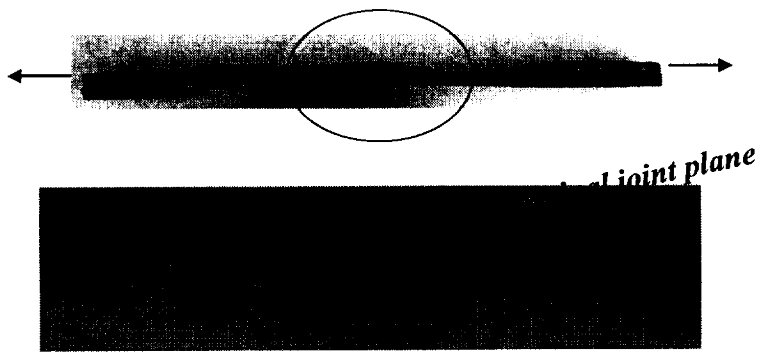
Tensile Specimen Geometry of Single Lap Joined MI SiC/SiC Composites



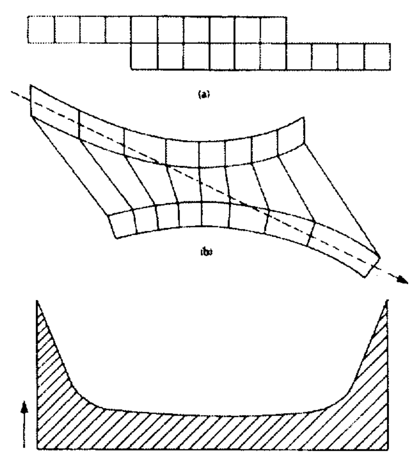
Tensile Stress vs Strain Behavior of Single Lap Joined MI SiC/SiC Composites



Fracture Behavior of Single Lap Joints in Melt Infiltrated SiC/SiC Composites

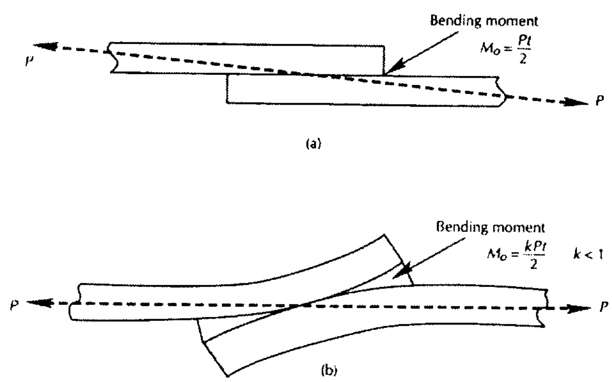


Shear Stress Distribution in a Single Lap Joint



(a) Subjected to shear stress; (b) Eccentric loading causes distortion; (c) Resulting stress distribution

Goland and Reissner's Bending Moment Factor in Single Lap Joints



Stress Distribution in Single Lap Joints Subjected to Tensile Loading

(Goland and Reissner)

The expressions for the adhesive and transverse stresses, normalized by the applied tensile stress, are:

$$\frac{\tau_o}{\sigma_{appl}} = -\frac{1}{8}\frac{t}{c}\left[\frac{\beta c}{t}(1+3k)\frac{\cosh\left(\frac{\beta c}{t}\frac{x}{c}\right)}{\sinh\left(\frac{\beta c}{t}\right)} + 3(1-k)\right] \quad \textbf{(1)}$$

$$\frac{\sigma_o}{\sigma_{appl}} = \frac{t^2}{c^2}\frac{1}{\Delta}\left[\left(R_2\lambda^2\frac{k}{2} + \lambda k'\cosh\lambda\cos\lambda\right)\cosh\left(\lambda\frac{x}{c}\right)\cos\left(\lambda\frac{x}{c}\right) + \left(R_1\lambda^2\frac{k}{2} + \lambda k'\sinh\lambda\sin\lambda\right)\sinh\left(\lambda\frac{x}{c}\right)\sin\left(\lambda\frac{x}{c}\right)\right] \quad \textbf{(2)}$$

Where

$$\beta^2 = \frac{8\, G_c\, t}{E\, \eta} = \frac{4\, E_c\, t}{E\, \eta\, (1 + \nu_c)} \quad (3)$$

$$M_o \approx k\, \frac{T\, t}{2} = \frac{k\, p\, t^2}{2} \quad (4)$$

$$k = \frac{1}{1 + 2\sqrt{2}\, \tanh\left(\frac{\xi\, c}{2\sqrt{2}}\right)} \quad (5)$$

$$\xi = \sqrt{\frac{12\, \left(1 - \nu^2\right) T}{E\, t^3}} \quad (6)$$

$$\gamma^4 = 6\, \frac{Ec}{E}\, \frac{t}{\eta} \quad (7)$$

$$\lambda = \gamma\, \frac{c}{t} \quad (8)$$

$$R_1 = \cosh \lambda \sin \lambda + \sinh \lambda \cos \lambda \quad (9)$$

$$R_2 = \sinh \lambda \cos \lambda - \cosh \lambda \sin \lambda \quad (10)$$

$$\Delta = \frac{1}{2}\left(\sinh\, 2\lambda + \sin\, 2\lambda\right) \quad (11)$$

Stress Distribution in Single Lap Joints Subjected to Tensile Loading

(Goland and Reissner)

The geometric and materials parameters c, t, E, ν, E_c, and ν_c are given below. Based on this analysis, the experimental tensile data, the geometry of the specimen, and the following elastic properties:

$E_{substrate}$ = 300 GPa (E)
$\nu_{substrate}$ = 0.15 (ν)
$E_{adhesive}$ = 350 GPa (E_c)
$\nu_{adhesive}$ = 0.2 (ν_c)

The maximum transverse and adherent shear stresses were found to be:

$$\frac{\tau_o}{\sigma_{appl}} = -4.2$$

$$\frac{\sigma_o}{\sigma_{appl}} = 5.5$$

Maximum Transverse and Joint Shear Stresses in MI SiC/SiC Composites Obtained from Goland and Reissner Analysis

For Tensile Stresses of 45 and 42 MPa:

- **Shear Stress:**

  $\tau_0 = 4.2 \cdot \sigma_{appl}$

  189 MPa and 176.4 MPa

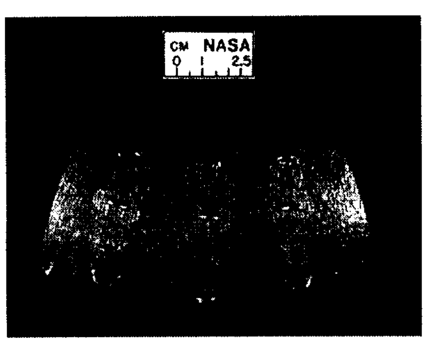
- **Transverse Stress:**

  $\sigma_0 = 5.5 \cdot \sigma_{appl}$

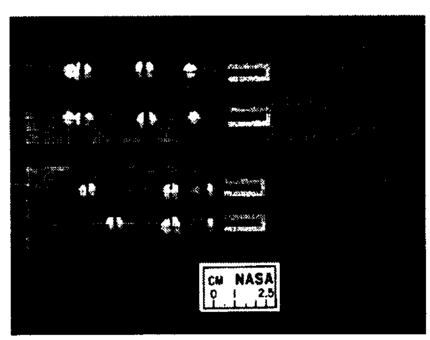
  247.5 MPa and 231 MPa

Application of ARCJoinT in Instrumentation Area

SiC Hoops Attached to SiC_f/SiC Composite Subelement Having a Curved Surface

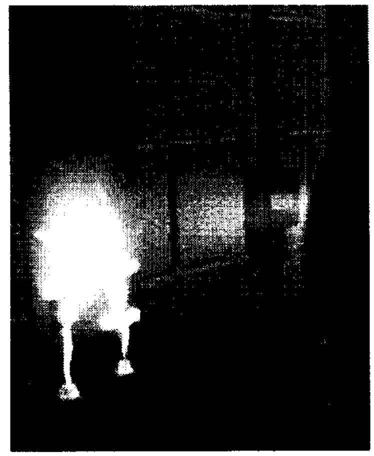


SiC_f/SiC Panels Instrumented With Thin Film Thermocouples



Testing of Instrumented SiC_f/SiC Ceramic Matrix Composite (CMC) Panels in a Mach 0.3 Burner Rig

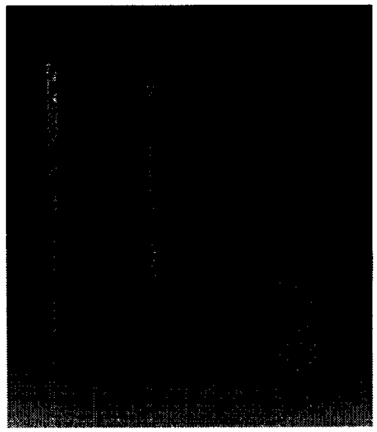
Burner rig testing of a CMC panel



Burner rig testing of the CMC panel with SiC_f/SiC attachments

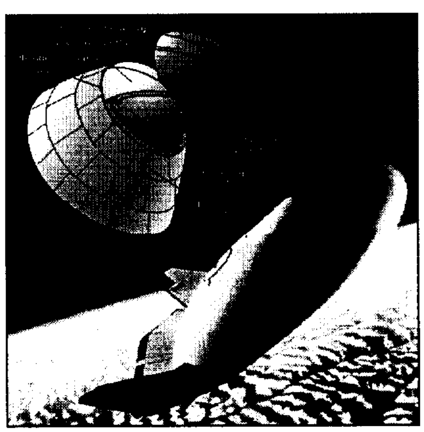
Application of ARCJoinT for Joining of SiC Tubes for Wafer Fabrication System at Trex Enterprises, Hawaii

Cabon-Carbon Composite Valves for Race Car Engines Joined Using ARCJoinT

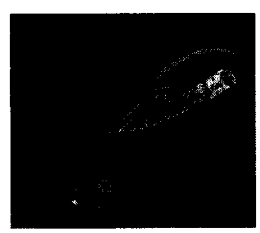


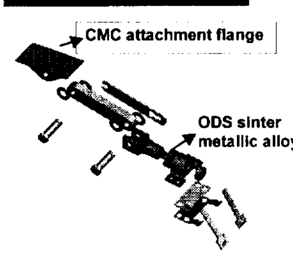
Joint Work with SGL Carbon-HITCO, Gardena, CA

Joining and Attachment Technologies are Key to Next Generation Space Transportation Systems (X-38)



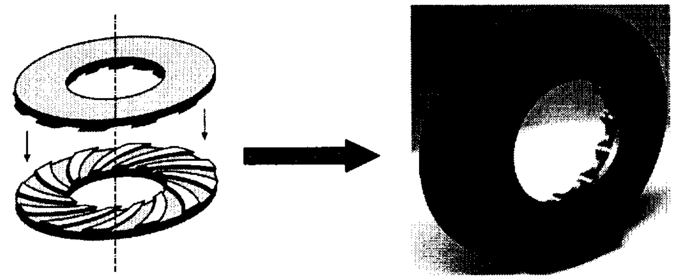
X-38 Demonstrator

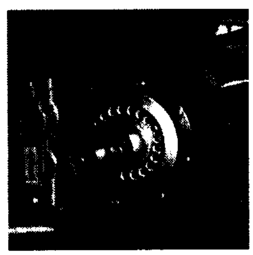


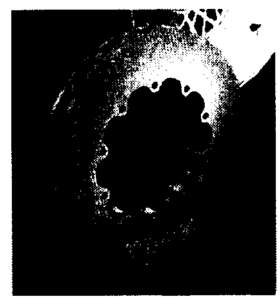


NASA-DLR-MAN Technology

Different Types of C-SiC Composite Automobile Brake Disks Manufactured Using Joining Technology

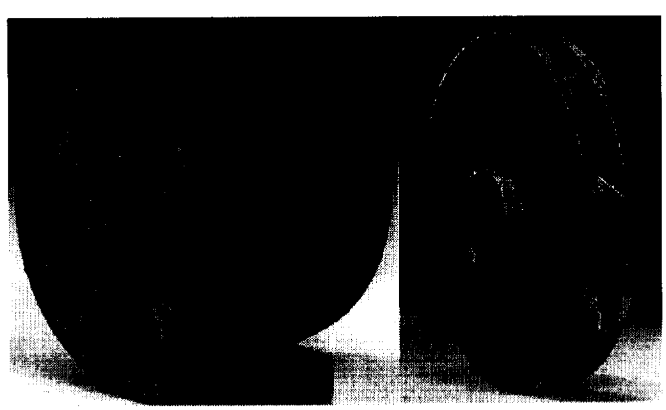






Dr. Walter Krenkel, DLR, Stuttgart, Germany

Heat Exchanger Substructure Made by Joining Eight Individual Plates and Design Study of a Radial Pump Wheel



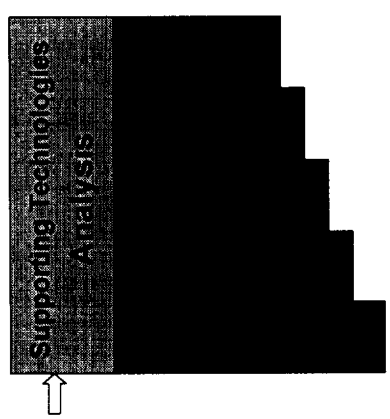
Heat Exchanger Substructure **Radial Pump Wheel**

Dr. Walter Krenkel, DLR, Stuttgart, Germany

Challenges in Joining of Ceramic Matrix Composites

- *Joint Design*
  - High elastic modulus of ceramic joint materials provide significant challenges to joint design and characterization.
  - Understanding of stress state in the joints.
- *Materials*
  - Optimization of in-plane tensile properties of CMCs by engineering the fiber/matrix interface are 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.
- *Applications*
  - Time dependent thermomechanical properties of joints.
  - Environmental effects on joint properties.

Opportunities to Utilize Building-Block Approach to Design and Manufacturing of Composite Structures



Design Considerations

Summary and Conclusions

- ARCJoinT has been used to produce strong ceramic joints with good microstructure and high temperature properties in a wide variety of high temperature ceramics and fiber reinforced composites.
- 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.
- 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.