JOINING AND INTEGRATION OF SILICON CARBIDE FOR TURBINE ENGINE APPLICATIONS

ABSTRACT

The critical need for ceramic joining and integration technologies is becoming better appreciated as the maturity level increases for turbine engine components fabricated from ceramic and ceramic matrix composite materials. Ceramic components offer higher operating temperatures and reduced cooling requirements. This translates into higher efficiencies and lower emissions. For fabricating complex shapes, diffusion bonding of silicon carbide (SiC) to SiC is being developed. For the integration of ceramic parts to the surrounding metallic engine system, brazing of SiC to metals is being developed. Overcoming the chemical, thermal, and mechanical incompatibilities between dissimilar materials is very challenging. This presentation will discuss the types of ceramic components being developed by researchers and industry and the benefits of using ceramic components. Also, the development of strong, crack-free, stable bonds will be discussed. The challenges and progress in developing joining and integration approaches for a specific application, i.e. a SiC injector, will be presented.

Joining and Integration of Silicon Carbide for Turbine Engine Applications

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MS&T'10, Materials Science & Technology 2010 Conference & Exposition,
Houston, TX, October 17-21, 2010.

Outline

- **Background - Objectives, Challenges, and Applications**
- **Processing, Characterization, and Results**
  - **Ceramic to Ceramic Joining: Diffusion Bonding of SiC to SiC**
  - **Ceramic to Metal Joining: Brazing of SiC to Kovar and to Molybdenum**
- **Conclusions**

Research Scope

Overall Objective: Deliver the benefits of ceramics in turbine engine applications- increased efficiency, performance, horsepower, range, operating temperature, and payload and reduced cooling and operation and support costs for future engines.

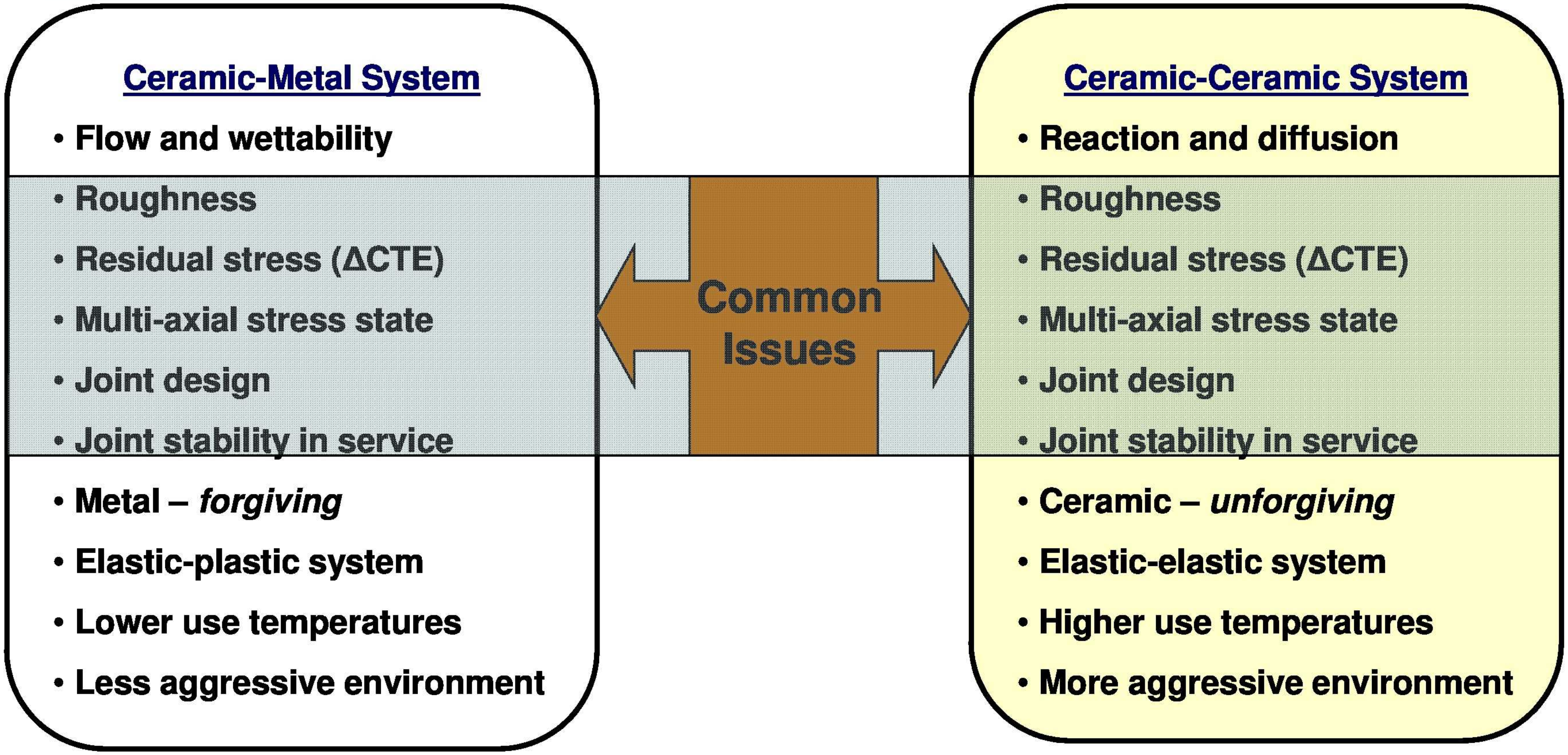
Targeted Components: Aeronautic and ground based engine applications: ceramic turbine vanes, blades, injectors, rotors, combustor liners, valves, and heat shields

Approach:

- Develop **ceramic to ceramic** joining technologies that enable the fabrication of complex shaped ceramic components.
  - Fabricated ceramic shapes are currently limited to relatively small, flat, and circular shapes due to limitations in ceramic processing methods (i.e. chemical vapor deposition and hot pressing).

- Develop **ceramic to metal** joining technologies that enable ceramic components to be integrated into metallic based engine systems.
  - Barriers to ceramic utilization are due to residual stresses and chemical and thermal incompatibility between ceramics and metals.

Technical Challenges in Integration of Ceramic-Metal *vs* Ceramic-Ceramic Systems



Ceramic-Metal System

- **Flow and wettability**
- **Roughness**
- **Residual stress (ΔCTE)**
- **Multi-axial stress state**
- **Joint design**
- **Joint stability in service**
- **Metal – *forgiving***
- **Elastic-plastic system**
- **Lower use temperatures**
- **Less aggressive environment**

Common Issues

Ceramic-Ceramic System

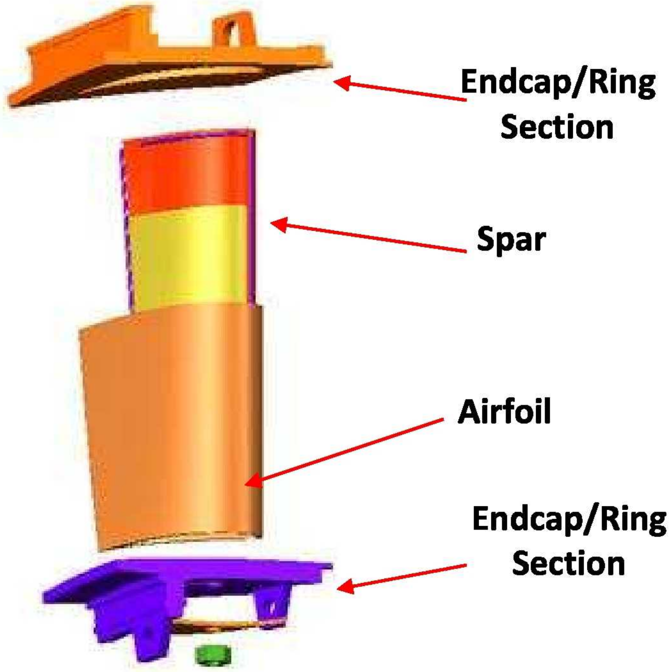
- **Reaction and diffusion**
- **Roughness**
- **Residual stress (ΔCTE)**
- **Multi-axial stress state**
- **Joint design**
- **Joint stability in service**
- **Ceramic – *unforgiving***
- **Elastic-elastic system**
- **Higher use temperatures**
- **More aggressive environment**

Joining Challenges

- Thermal, chemical, and mechanical incompatibilities between the different materials
- Obtaining bonds that are high strength, leak free, and stable
- Non-wetting of ceramics during brazing and interlayer flow with other processing methods
- Cracking in the bond layers and/or substrates
- Lack of ASTM standards for mechanical tests

Joining Applications for SiC Based Turbine Engine Components

Hybrid Vane for HPT



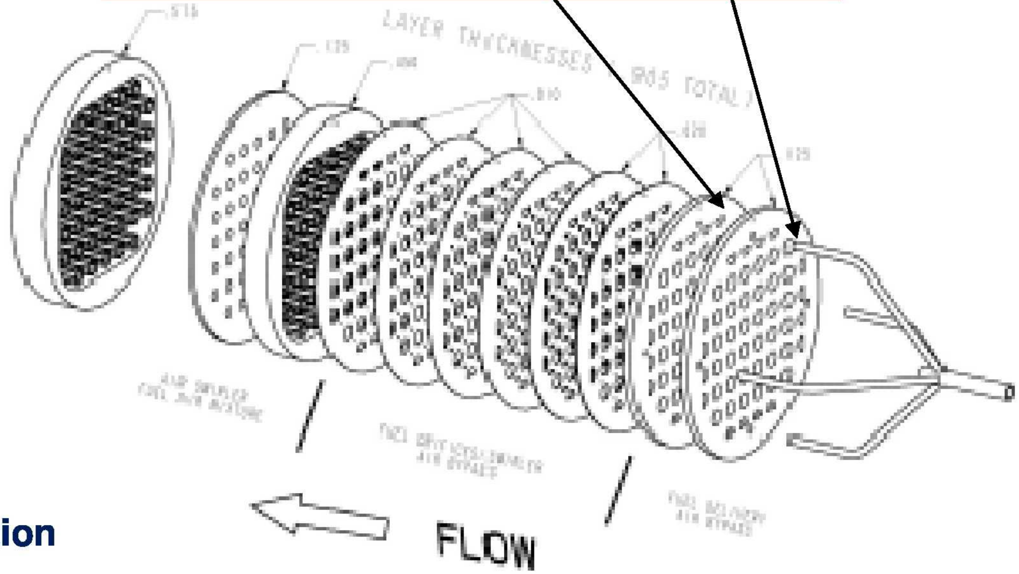
Develop and characterize the joining and integration technologies required for a hybrid vane:

- **Joining the airfoil to the endcap**
- **Joining for ceramic to metal integration**
- **Joining of singlet vanes to from doublets**

Fabrication and Testing of a MEMS Lean Direct Injector

Key Enabling Technologies:

- Brazing of SiC to Metallic Fuel Tubes
- Bonding of SiC to SiC



R. Tacina et al., TM-2002-211347

Develop and characterize the joining and integration technologies required for injector fabrication:

- **Diffusion Bonding of SiC Laminates**
- **Brazing Metallic Tubes to SiC**

Integration Technologies for MEMS-LDI Fuel Injector

Advantages of Lean Direct Injector (LDI) Design

-Does not have the problems of Lean Pre-Mixed Pre-Evaporated Injector such as auto-ignition and flashback)

- Provides extremely rapid mixing of the fuel and air before combustion occurs

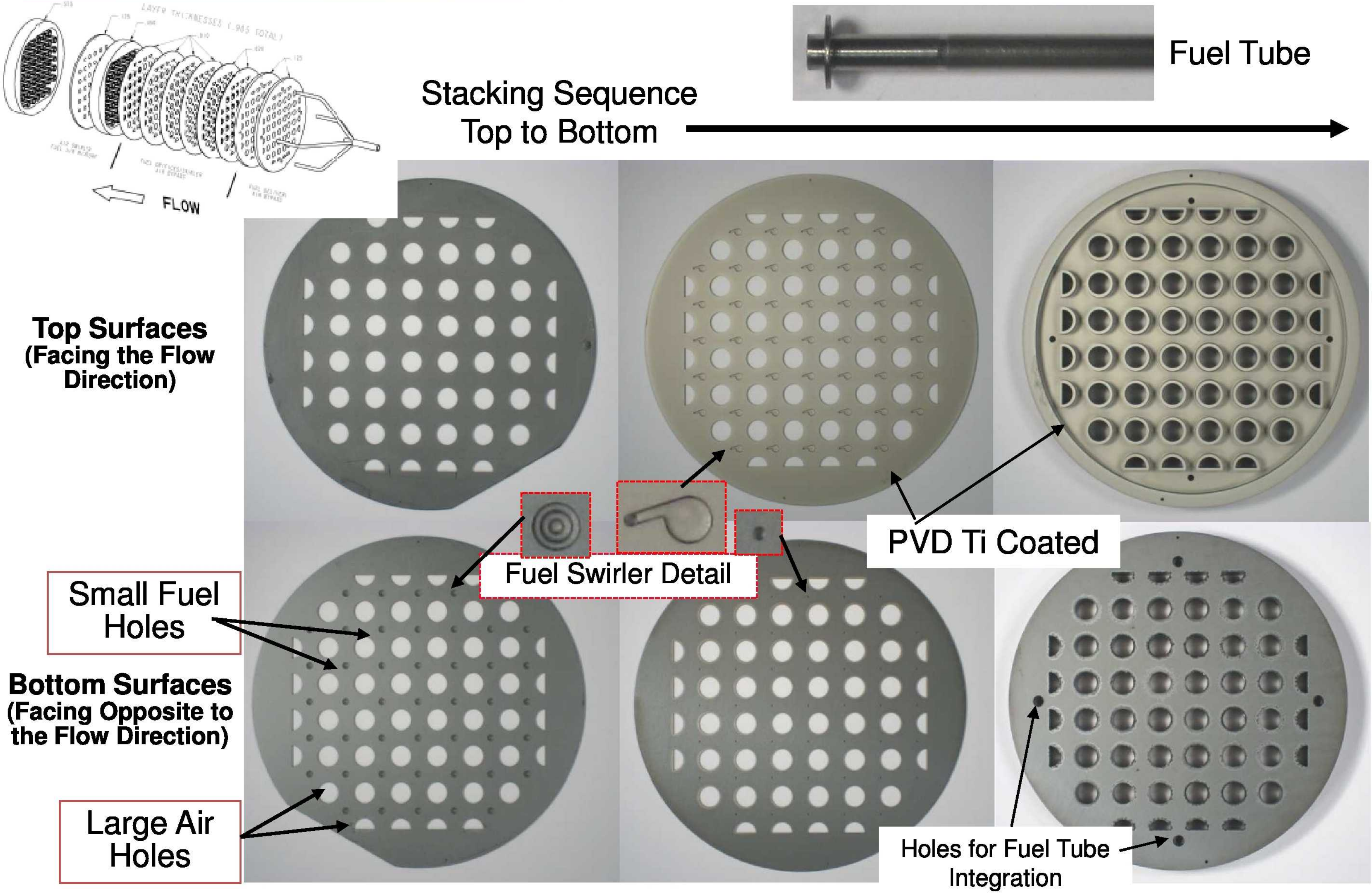
Objective: Develop Technology for a SiC Smart Integrated Multi-Point Lean Direct Injector (SiC SIMP-LDI)

- Operability at all engine operating conditions
- Reduce NOx emissions by 90% over 1996 ICAO standard

Silicon Carbide Design Despite Being a Low Temperature Application (~400ºC)

- Allows for integration of silicon carbide based high frequency fuel actuators and sensors
- Passages of any shape can be created to allow for multiple fuel circuits
- Provides thermal protection of the fuel to prevent coking
- Allows for low cost fabrication of modules with complicated internal geometries through chemical etching
- Allows for a non-flowing reaction bonded joining approach that won’t clog the fuel and swirler holes

Joining Applications
– Detail of the Three Part 10 cm (4”) Diameter SiC Injector



Fuel Tube

Stacking Sequence
Top to Bottom

Top Surfaces
(Facing the Flow Direction)

Fuel Swirler Detail

PVD Ti Coated

Small Fuel Holes

Bottom Surfaces
(Facing Opposite to the Flow Direction)

Large Air Holes

Holes for Fuel Tube Integration

Stacking Sequence Bottom to Top

Experimental Procedure -
Ceramic to Ceramic and Ceramic to Metal Joining

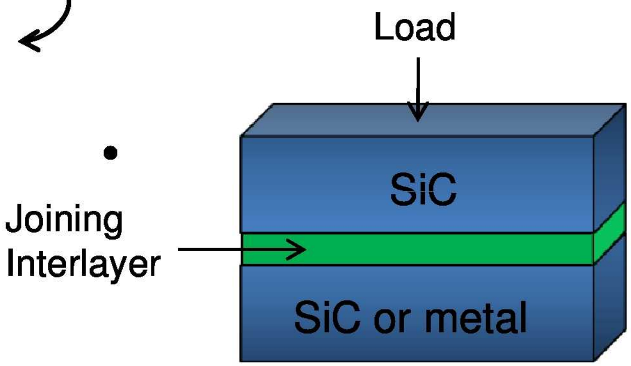
JOINING PROCESS

- Ceramic and metal substrates were ultrasonically cleaned in Acetone for 10 minutes
- Substrates were sandwiched around braze and foil layers

Materials (dimensions 0.5" x 1")
- Substrate: CVD SiC (Rohm & Haas)
- Interlayers: Ti foil (10, 20 micron) and B-Mo alloy foil (25 micron)

Diffusion Bonding

- Atmosphere: Vacuum
- Temperature: Ti 1200ºC, Mo 1400ºC
- Pressure: 30MPa
- Duration: Ti 1, 2, 4 hr B-Mo 4 hr
- Cool down: 2 ºC/min

- 

Materials (dimensions 0.5" x 1")
- Substrate: CVD SiC (R & H)
  - molybdenum and kovar
- Interlayer: Copper
- Braze layer: Cusil ABA (foil and paste)

Brazing

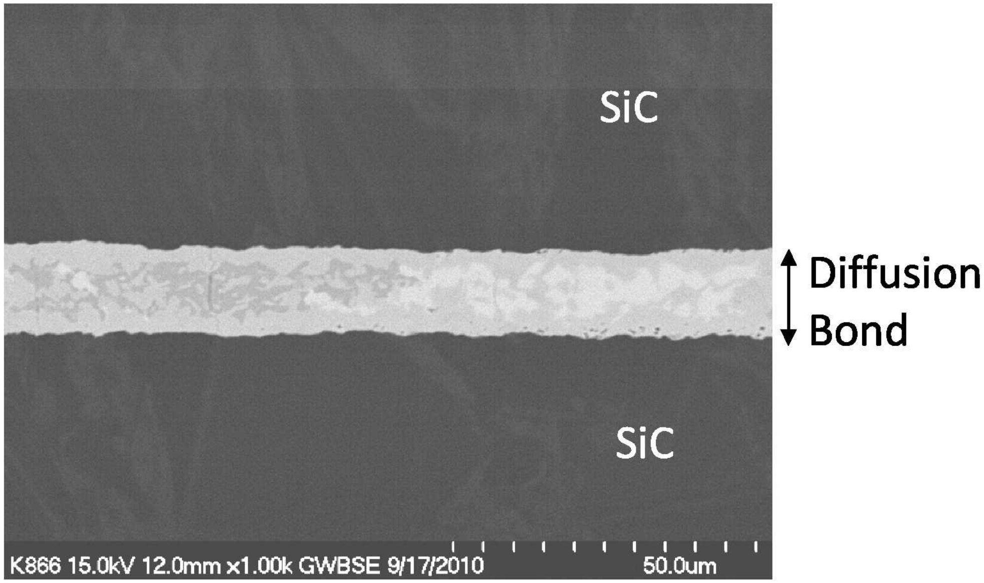
- Atmosphere: Vacuum
- Temperature: 825ºC (5 C above the braze liquidus Temperature)
- Load: 100 g/sample
- Duration: 5 minutes
- Cool down: 2 ºC/min

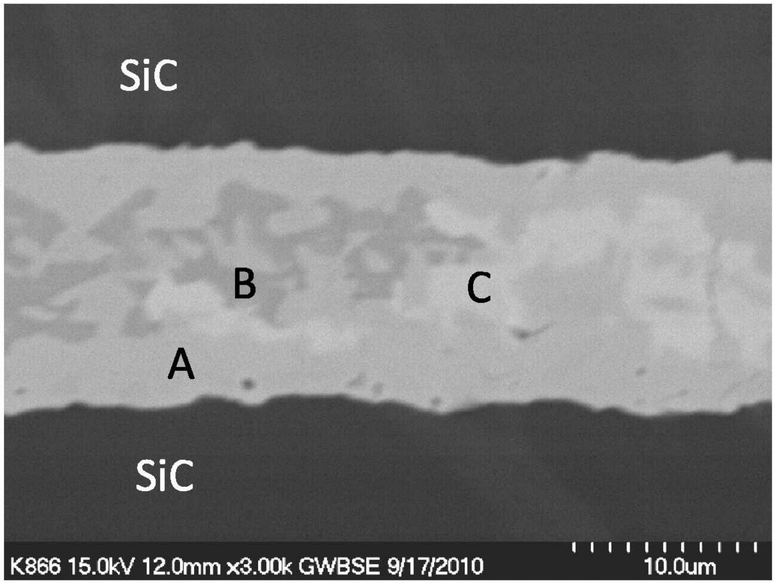
- Mounted in epoxy, polished, and joints characterized using optical and scanning electron microscopy with energy dispersion spectroscopy analysis and microhardness testing

Material	Comp wt %
Cusil-ABA	63 Ag, 35.25 Cu 1.75Ti
Kovar	54 Fe, 29 Ni, 17 Co

Ceramic to Ceramic Joining
- Diffusion Bonding SiC to SiC

Diffusion Bonds from 10 µm Ti Foil at 1200ºC – 2 hr hold



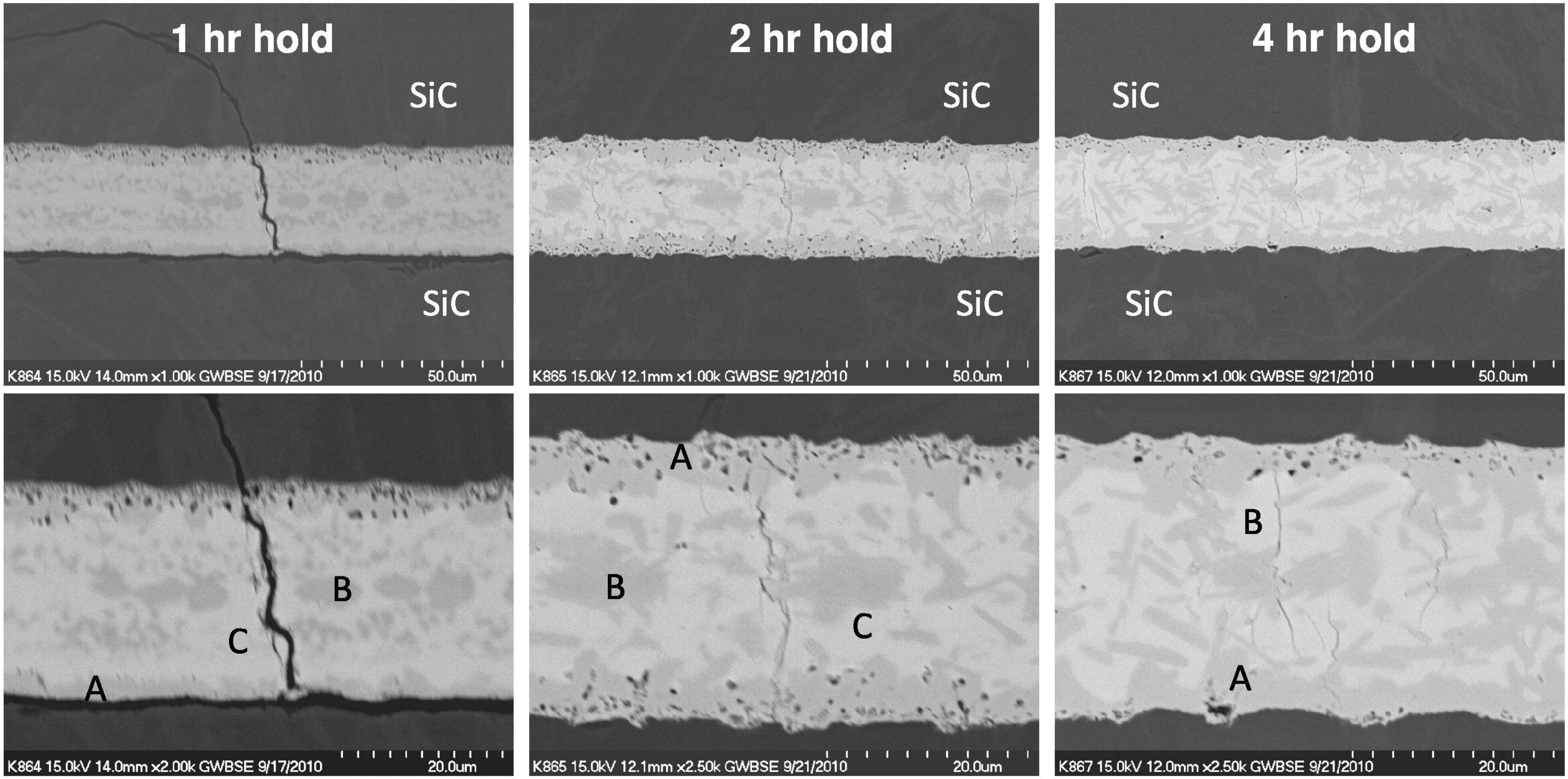


Very minimal microcracking cracking does not traverse through the thickness of the bond. Three reaction formed phases are observed in the diffusion bond.

	C	Si	Ti
Phase A	51	14	35
Phase B	37	43	20
Phase C	38	27	35

In atomic percent

Diffusion Bonds from 20 µm Ti Foil at 1200ºC



	C	Si	Ti
Phase A	54	13	33
Phase B	57	1	42
Phase C	44	23	33

In atomic percent

	C	Si	Ti
Phase A	55	13	32
Phase B	58	7	35
Phase C	47	22	31

In atomic percent

	C	Si	Ti
Phase A	53	14	33
Phase B	42	25	33

In atomic percent

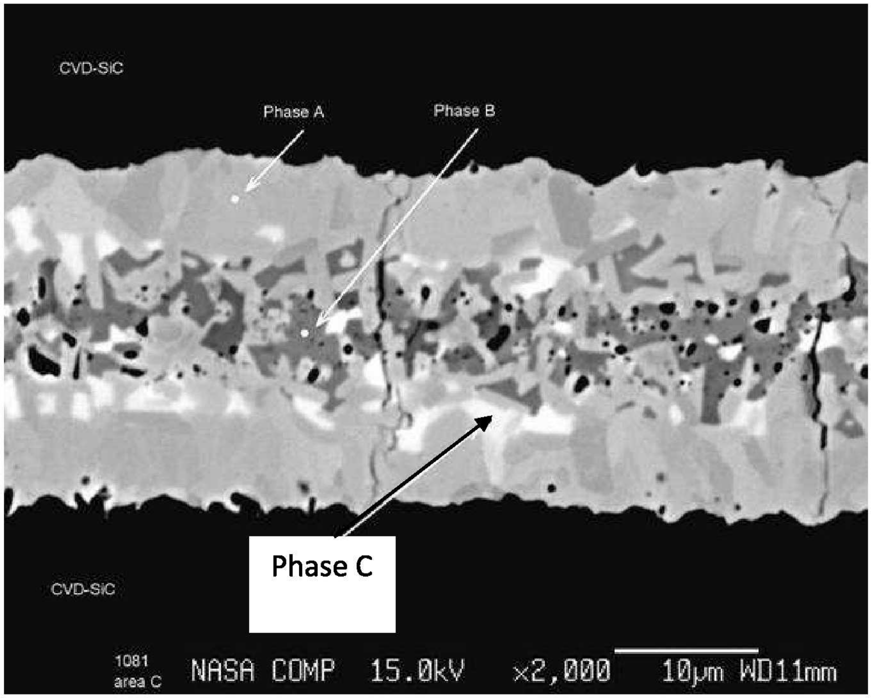
Microcracking is lessened as titanium carbide at the core is reacted away.

Diffusion Bonds Using PVD Ti as the Interlayer

20 Micron Ti Interlayer, 1250ºC, 2 HR

Microcracking is still present due to the presence of Ti5Si3CX.

Naka et al suggest that this is an intermediate phase.



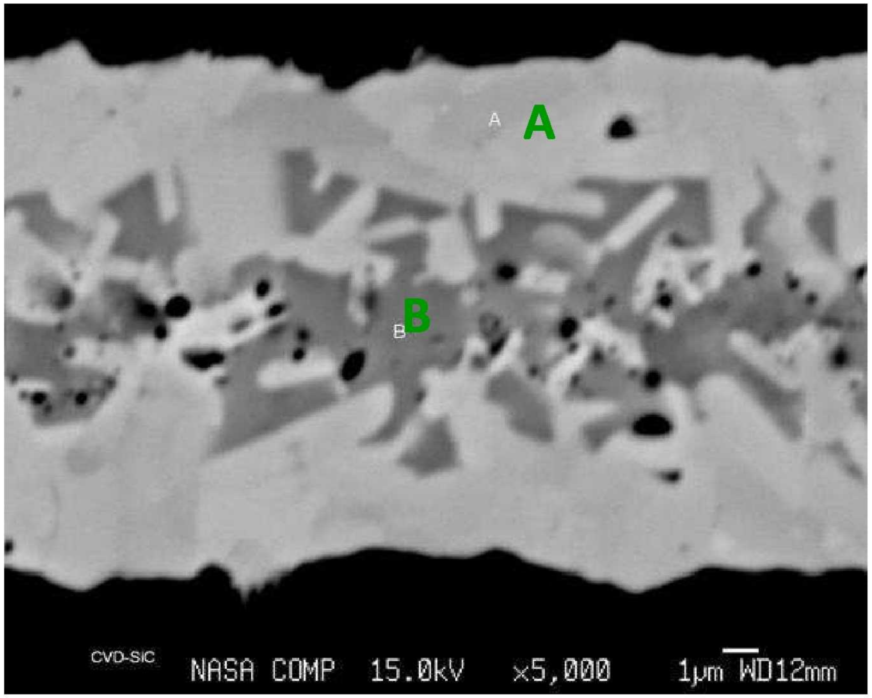
Phases in bond with the 20 μ Ti Interlayer – Atomic Percent

Phase	Ti	Si	C
Phase A	56.426	17.792	25.757
Phase B	35.794	62.621	1.570
Phase C	58.767	33.891	7.140

10 Micron Ti Interlayer , 1250ºC, 2 HR

No microcracking or phase of Ti5Si3CX is present.

Thin interlayers of pure Ti down-selected as the preferred interlayer.

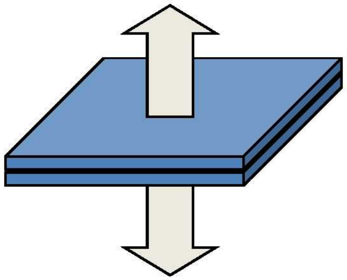


Phases in bond with the 10 μ Ti Interlayer – Atomic Percent

Phase	Ti	Si	C
SiC	0.011	54.096	45.890
Phase A	56.621	18.690	24.686
Phase B	35.752	61.217	3.028

High Strength of Bonds Exceed the Application Requirements

1” x 1” Bonded Substrates



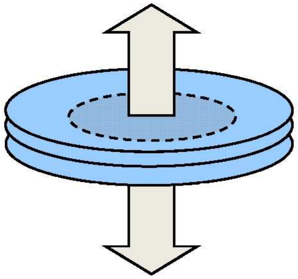
Pull test tensile strengths:

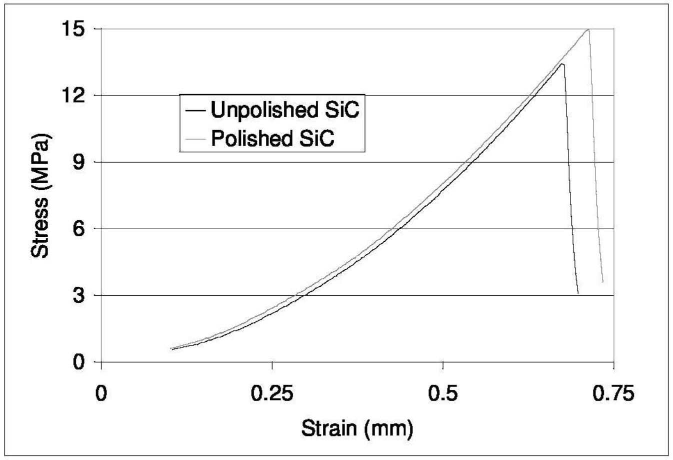
> 23.6 MPa (3.4 ksi)*

> 28.4 MPa (4.1 ksi)*

* failure in the adhesive to the test fixture

1” Diameter Discs with a 0.65” Diameter Bond Area





Pull test tensile strengths:

13.4 MPa (1.9 ksi)

15.0 MPa (2.2 ksi)

Slightly higher strength from the highly polished SiC suggests that a smoother surface contributes to stronger bonds or less flawed SiC.

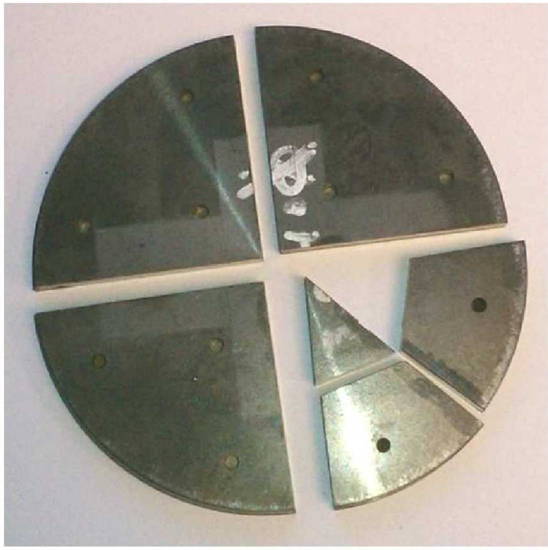
Failures are primarily in the SiC substrate rather than in the bond area.

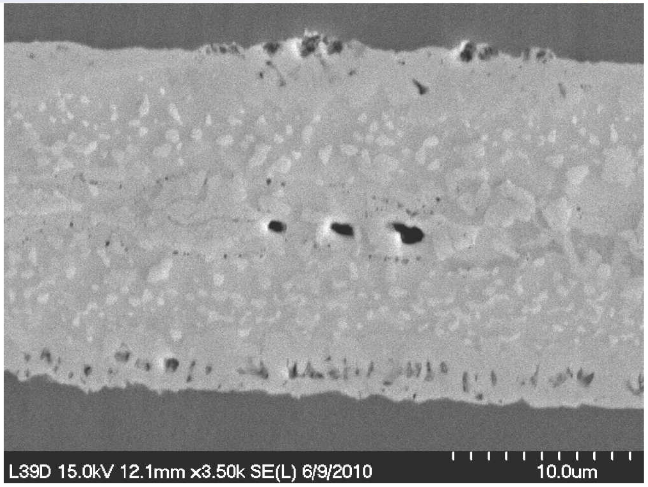
The injector application requires a strength of about 3.45-6.89 MPa (0.5 - 1.0 ksi).

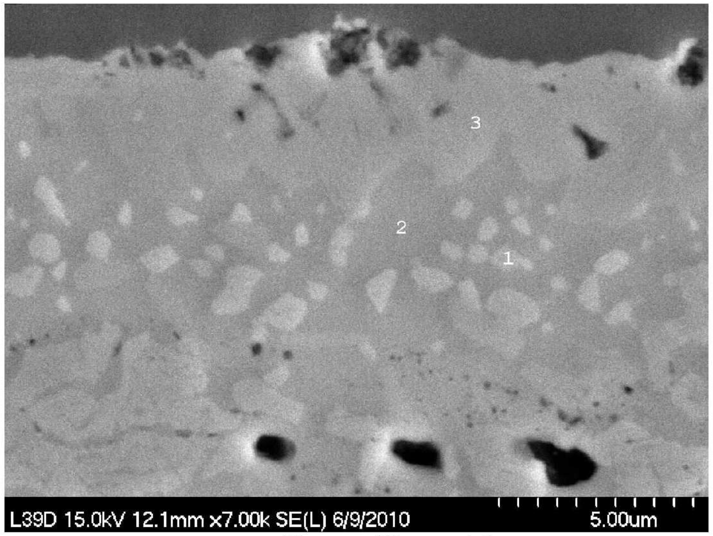
Demonstration of Diffusion Bonding on 4” Diameter CVD SiC Discs

Joined 4” diameter SiC discs.

Sectioned for microscopy and to demonstrate leak free at bonded and machined edges.





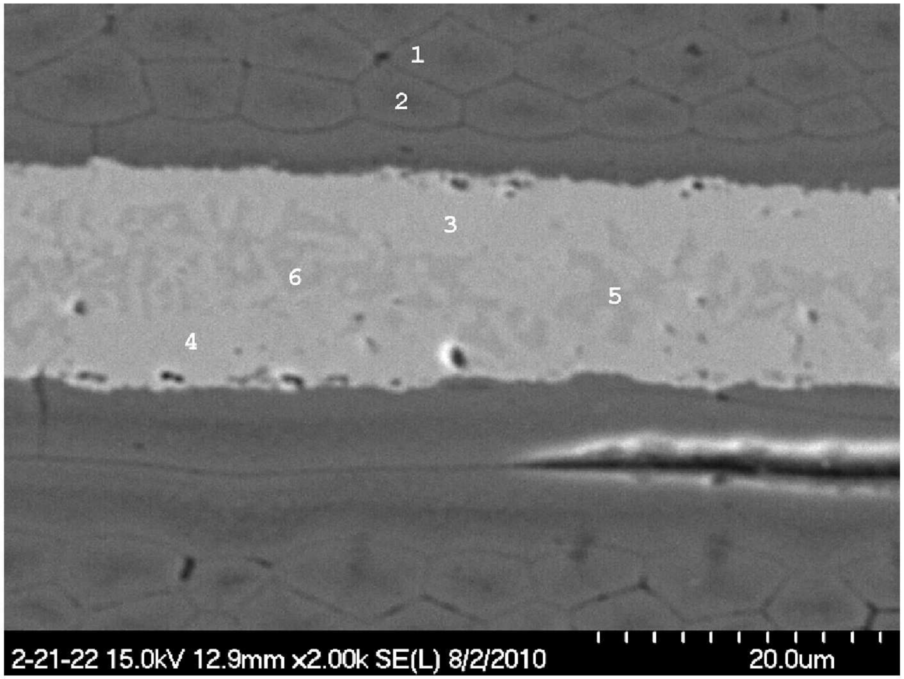


	C	Si	Ti
Phase 1	57	9	34
Phase 2	34	28	38
Phase 3	50	14	36

In atomic percent

Diffusion Bonding of 8 HS SA-Tyrannohex with 10 µm Ti Foil and 25 µm Boron-Molybdenum Alloy Foil

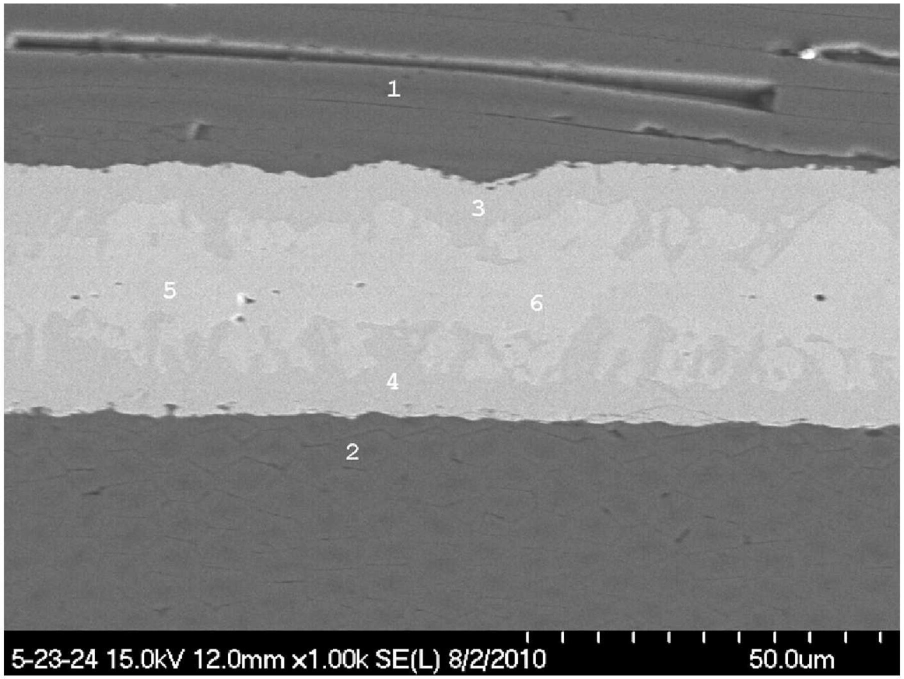
SA-Tyrannohex / **Ti** / SA-Tyrannohex



	C	Si	Ti
1	54.28%	45.72%	0%
3	44.89%	15.79%	39.33%
5	0%	69.39%	30.61%

Percents are atomic %

SA-Tyrannohex / **B-Mo alloy** / SA-Tyrannohex



	C	Si	B	Mo	O
1	58.34%	41.66%	0%	0%	0%
3	19.09%	5.51%	63.96%	8.25%	3.19%
5	0%	0%	89.18%	10.82%	0%

Percents are atomic %

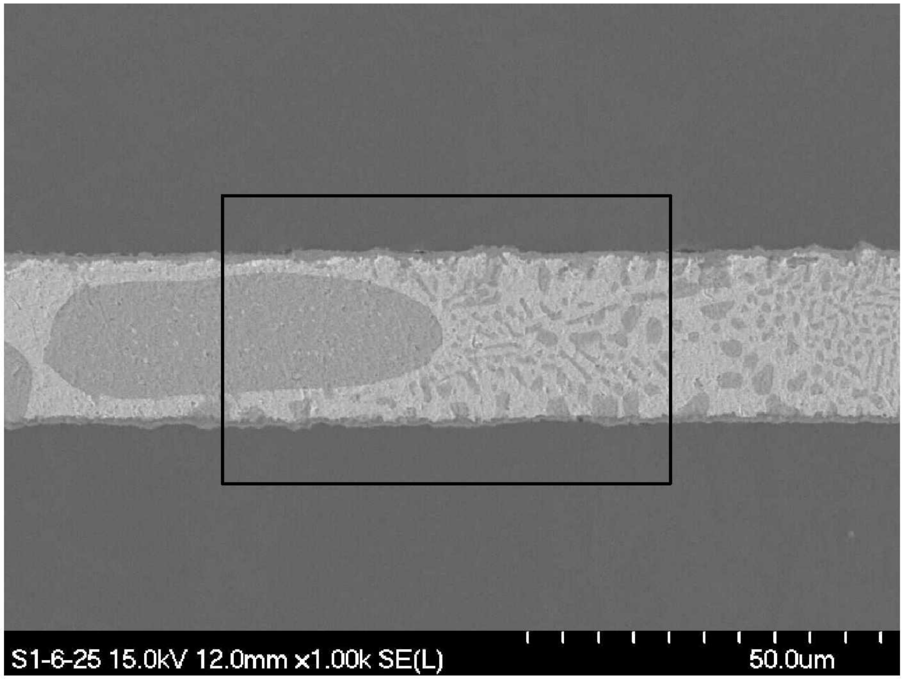
Ceramic to Metal Joining
- Brazing SiC to Kovar and to Molybdenum

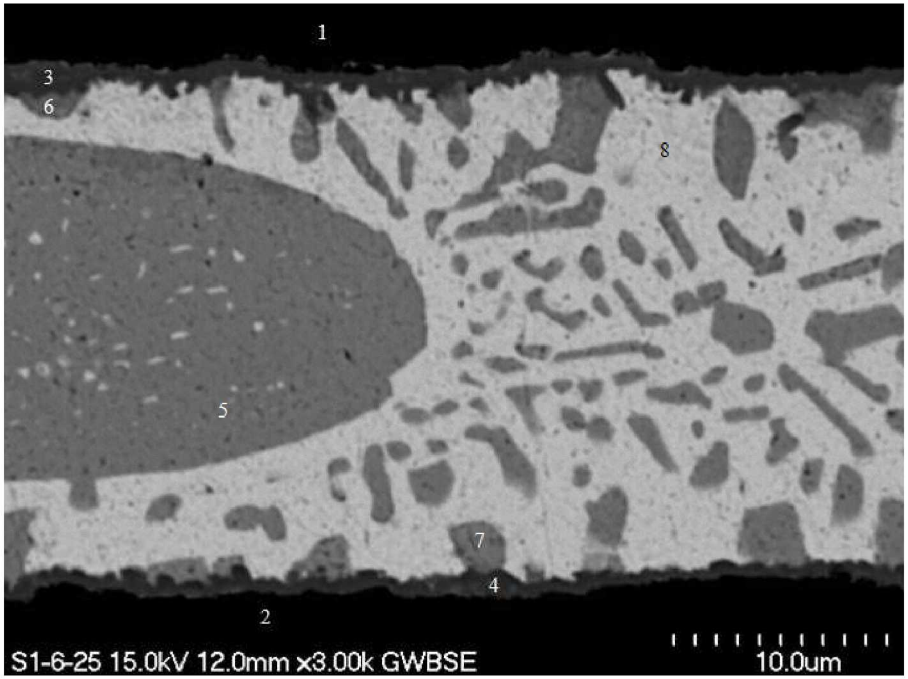
First, investigated **SiC to SiC** Brazing.

Then, investigated **SiC to metal** Brazing.

Brazing of SiC to SiC with Cusil ABA Foil

Brazing to ceramic is more challenging than brazing to metal.





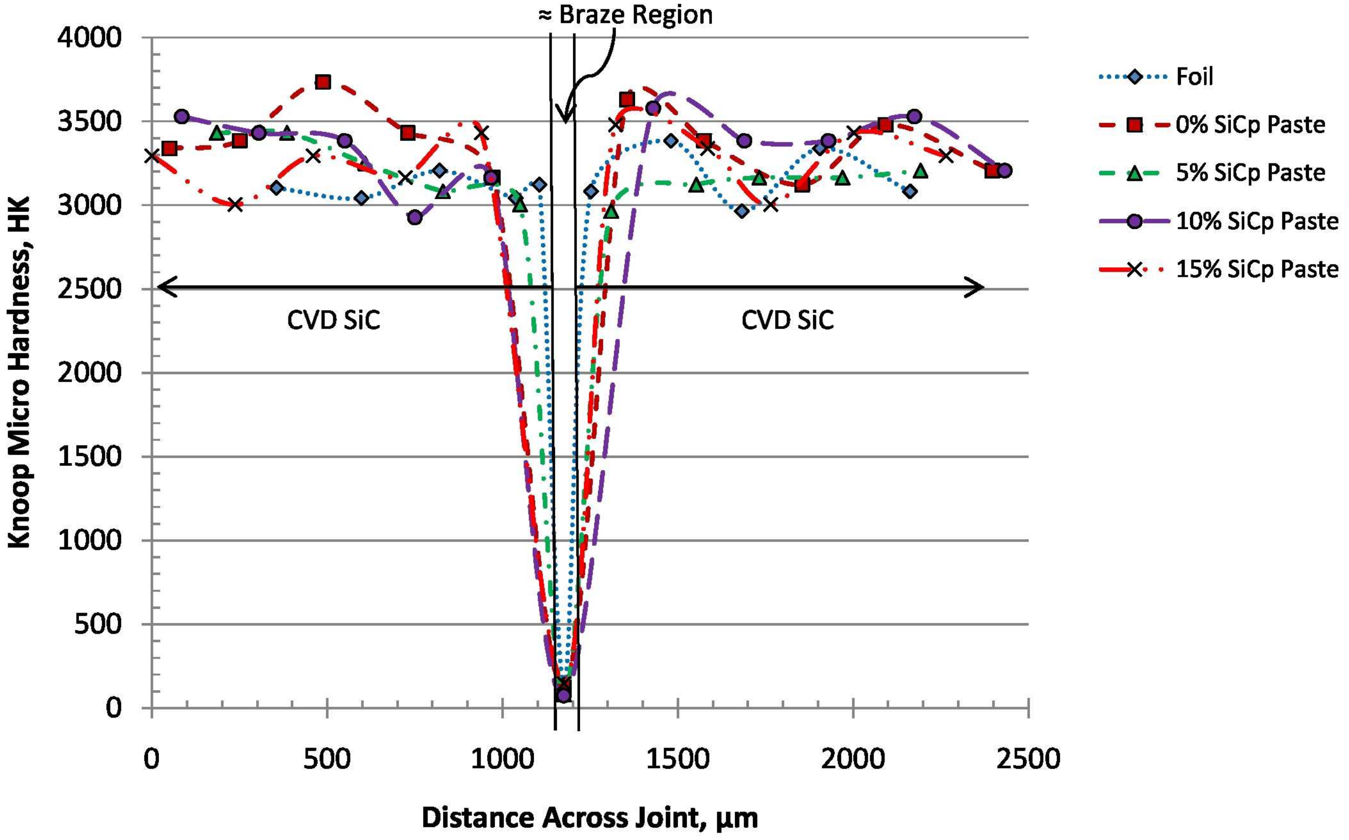
Demonstrates good wetting of the ceramic, the formation of reacted phases, and stress free, uncracked SiC substrates.

Relative atomic percentages among alloying elements for the SiC/Cusil ABA foil/SiC joint

	C	Si	Cu	Ag	Ti	O	N	B	Total
Point 1	52.2	47.8	-	-	-	-	-	-	100
Point 2	52.5	47.5	-	-	-	-	-	-	100
Point 3	52.48	5.09	3	0.76	38.67	-	-	-	100
Point 4	46.7	15.84	2.9	0.68	31.34	-	2.54	-	100
Point 5	-	-	100	-	-	-	-	-	100
Point 6	47.3	1.3	45.77	1.17	-	4.46	-	-	100
Point 7	-	-	100	-	-	-	-	-	100
Point 8	24.51	-	2.32	17.45	-	-	-	55.72	100

Brazing of SiC to SiC Using Cusil ABA Paste With SiC Particle Additions

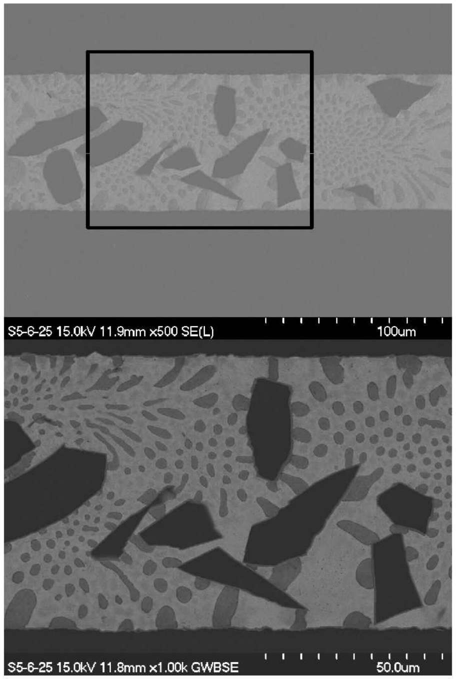
CVD SiC - Cusil ABA - CVD SiC Hardness Profile



SiC particle additions allow for tailorable ductile joints to alleviate stresses in the substrates

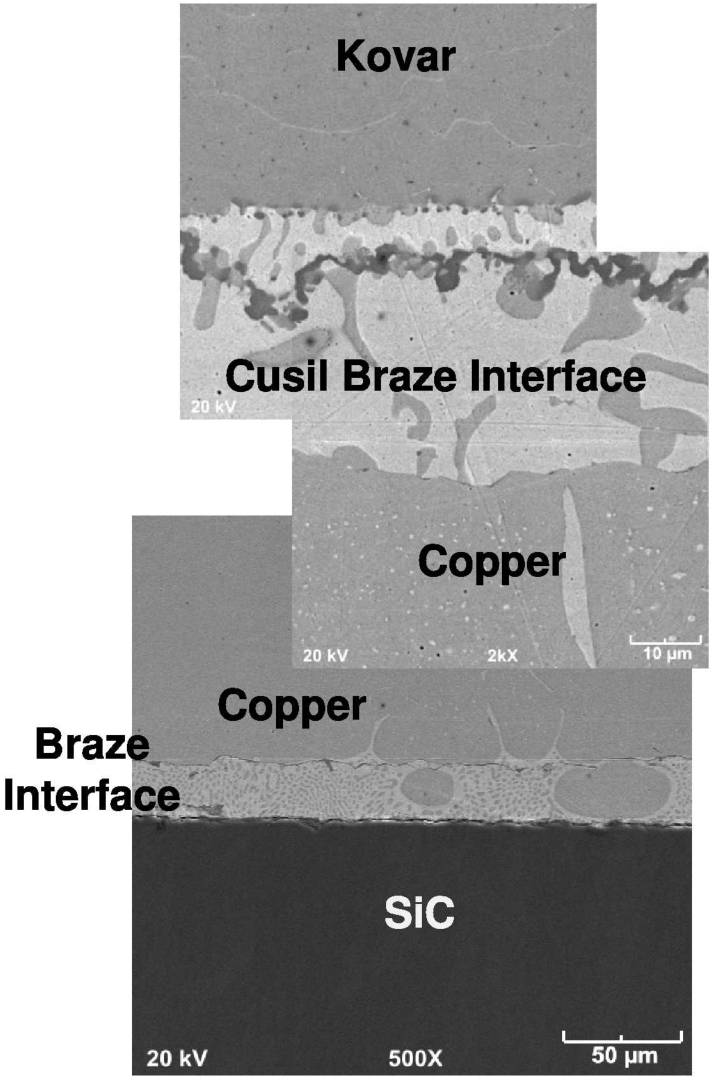
Mean (μ) & Standard Deviation (σ) of CVD SiC - CVD SiC Joints										
			Cusil ABA Paste							
	Cusil ABA Foil		0% SiCp		5% SiCp		10% SiCp		15% SiCp	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
CVD SiC	3103	60.7	3410.2	185.4	3239.2	175.6	3286.8	215.8	3237.2	144.4
Braze	142	32.5	127.7	3.3	80.9	7.7	74.9	11.3	147.8	67.0
CVD SiC	3170	162.4	3364.0	183.0	3124.0	84.3	3416.0	130.3	3309.0	166.4

Brazing with Cusil ABA Paste w/15 wt.% SiCp

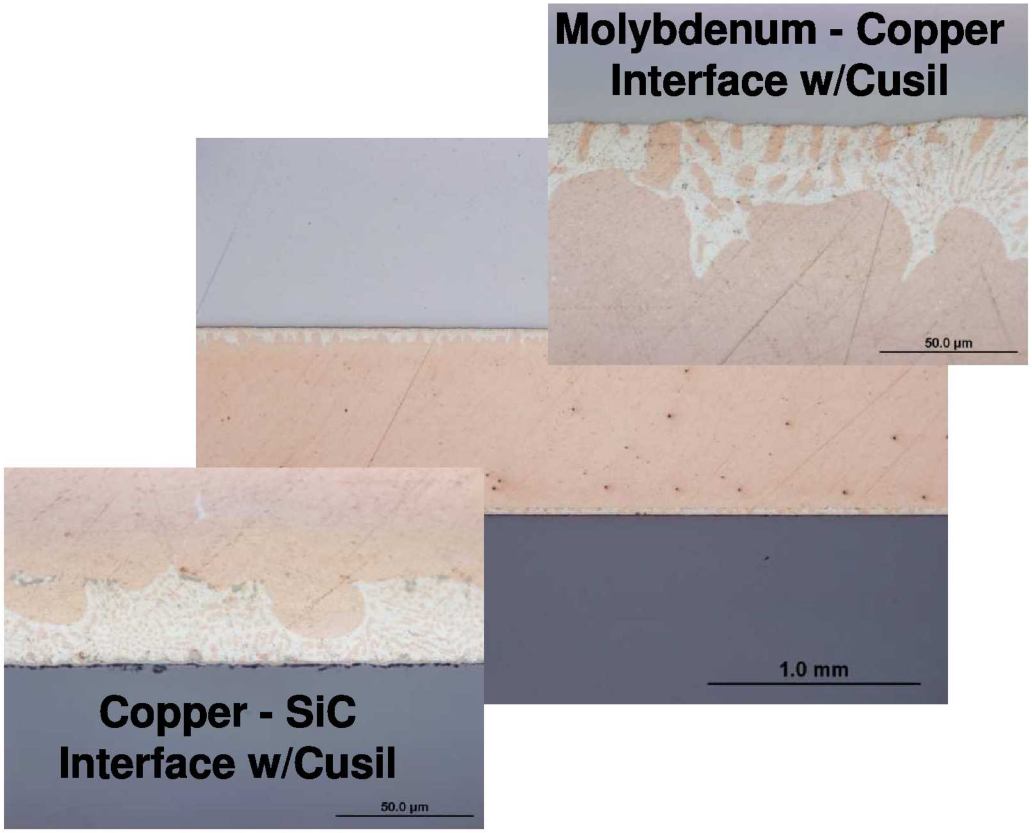


Brazing of SiC to Kovar and to Molybdenum with Cusil ABA Foil/Copper/Cusil ABA Foil

Kovar / Cusil ABA / Copper / Cusil ABA / SiC

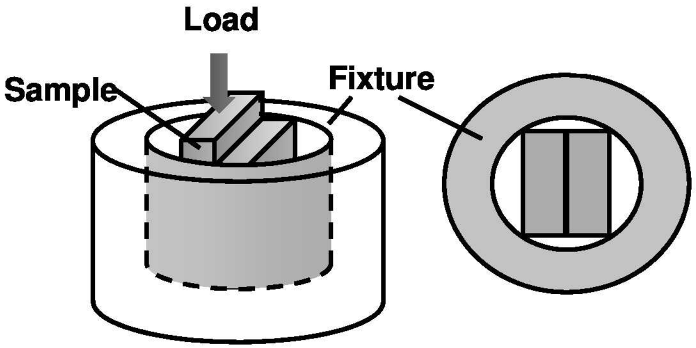


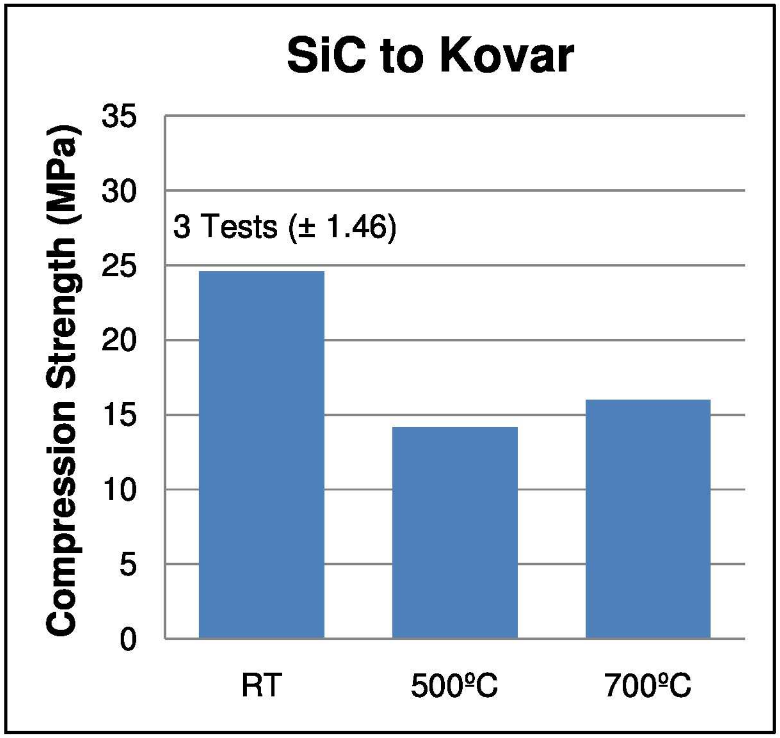
Molybdenum / Cusil ABA / Copper / Cusil ABA / SiC

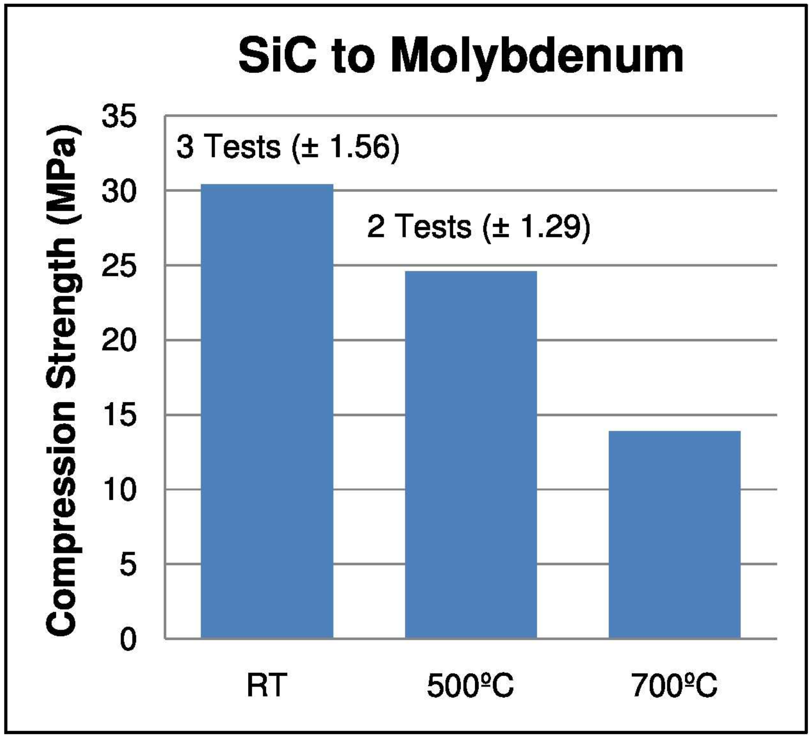


Single Lap Offset (SLO) Shear Testing - Brazes of SiC to Kovar and to Molybdenum with Copper and Cusil ABA Foil

- **Testing Conditions**
  - **Crosshead speed: 0.5mm/min**
  - **Air**
  - **RT, 500ºC, 700ºC**







Conclusions

- Joining approaches are being developed and optimized so that thermal stresses are relieved and microcracks do not form.

- Diffusion bonds fabricated with thinner interlayers of 10 micron thick Ti gave better diffusion bonds with little or no microcracking.

- Brazing SiC to metals using a multi-layer approach results in crack free bonds with high strength.
    - The addition of SiC particulates to the Cusil paste allows the properties to be modified.

- Joining approaches will enable the fabrication and utilization of ceramic components.

- The next steps are to further evaluate the mechanical and thermal performance of the joints and to fabricate and characterize the SiC injector.

Acknowledgements

- The NASA Subsonic Fixed Wing Project and Dr. Dan L. Bulzan and at NASA GRC for providing support.
- Dr. Robert Okojie of NASA GRC for providing PVD Ti Coated CVD SiC and for collaborating on the SiC injector application.
- Robert Angus for processing diffusion bonds in the hot press.