A RAPID PROCESSING METHOD FOR LARGE, LOW-EXPANSION, LIGHT-WEIGHT MIRRORS

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Technology Days in the Government Mirror Development
August 17-19, 2004, Huntsville, AL

M CUBED TECHNOLOGIES' (MCT) MISSION
BE A LEADER IN SUPPLYING TECHNICAL SOLUTIONS
FOR APPLICATIONS NEEDS OF GLOBAL CUSTOMERS
USING ADVANCED METALS, CERAMICS & COMPOSITES
PROVIDING THEM COMPETITIVE ADVANTAGE
THROUGH ENHANCED PERFORMANCE AND LOWER COST

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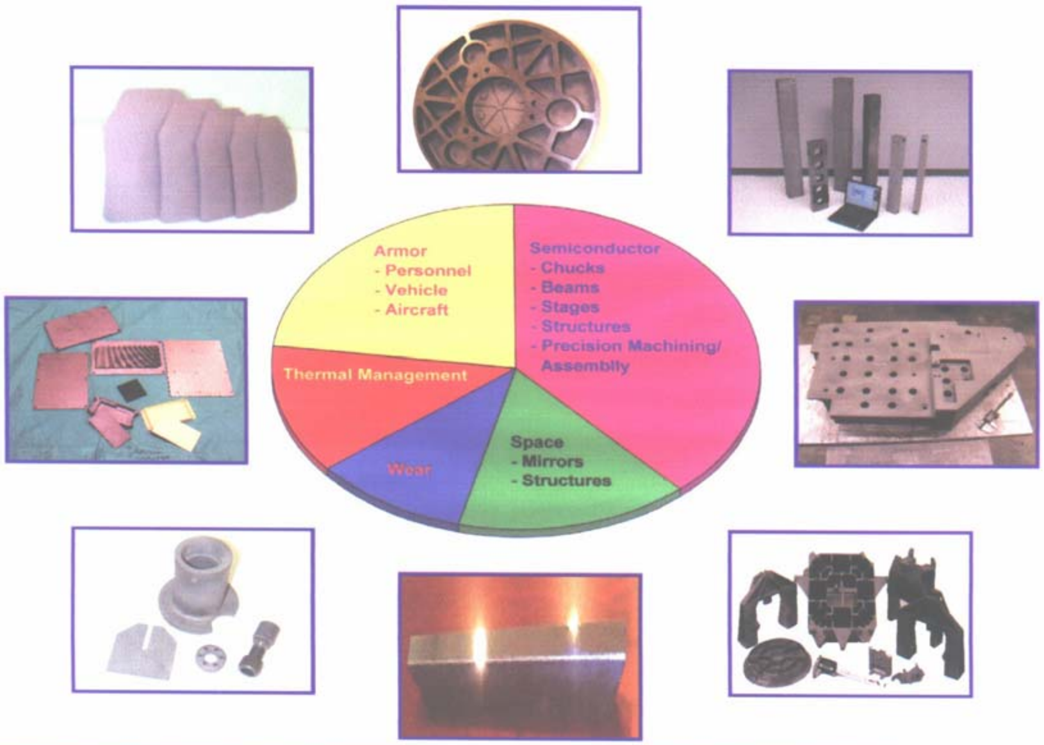
NEW MATERIALS FOR A NEW AGE



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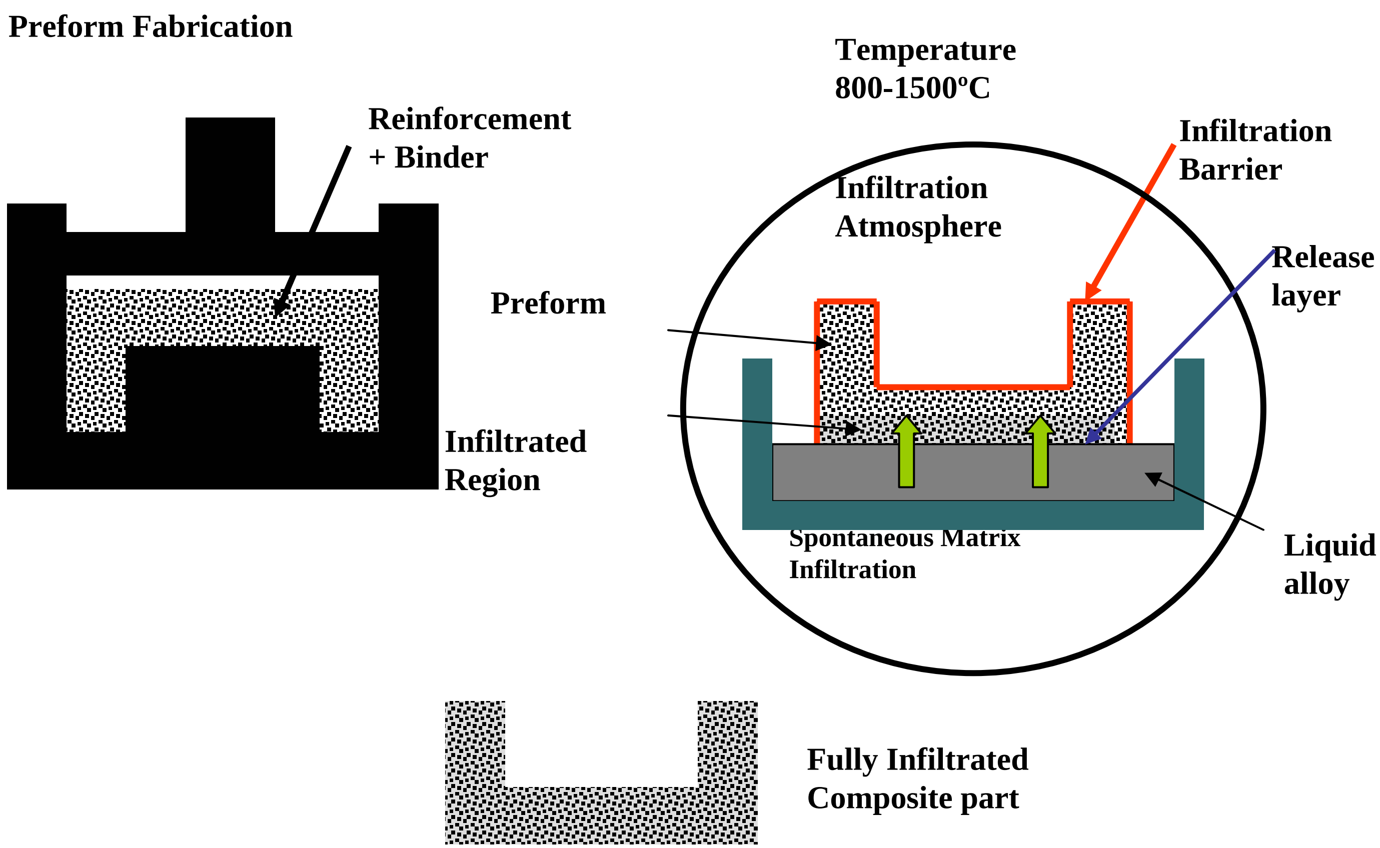
Mirrors and Structures Applications: Requirements

Material	ρ (g/cc)	α (ppm/K)	k (w/mK)	E (GPa)	Fract. Tough. (MPa/m1/2)	UBS or (UTS) (MPa)	E/ ρ	k/ α	Stren-gth/ ρ	Polish - ability
Al	2.7	27	237	70	20	270	26	8.8	100	Fast
Be	1.85	11.4	150	300	10	(324)	162	13.1	(175)	Slow
Si	2.33	2.6	150	120	1-2	50-80	52	58	22	Fast
CVD SiC	2.95	2.4	175	364	4	450	123	73	150	Slow
ULE	2.2	0.03	1.3	73	1-2	50-90	33	43	23	Fast
Zerodur	2.55	0.05	1.6	80	1-2	50-90	36	39	20	Fast
Silica	2.2	0.65	1	70	1-2	32	30	3	15	Fast
MCT Materials	Application Criteria: Blue- Strength; Pink- Sp. Stiffness & Thermal Stability; Green-Sp. Stiffness; Orange- All[$]									
Al/SiC (55)	2.95	10	180	200	11	(340)	68	18	(115)	Fast*
Al/SiC (70)	3.01	4.1	170	270	10	(230)	90	41	(77)	Fast*
Si/SiC (80)	3.03	2.9	185	380	4	290	125	64	96	Fast*
Si/B_4C (70)	2.57	4.0	100	382	4.8	271	149	25	105	Fast*
C_f/SiC**	2-2.4	-0.5-2.0	100-200	100-300	4-10	100-400	50-150	>150	50-160	Fast*

$- With development, * - With a coating ** - Tailorable by choosing fiber and interface

Pressureless Infiltration Processes: PRIMEX and Reaction Bonding



Reaction Bonding

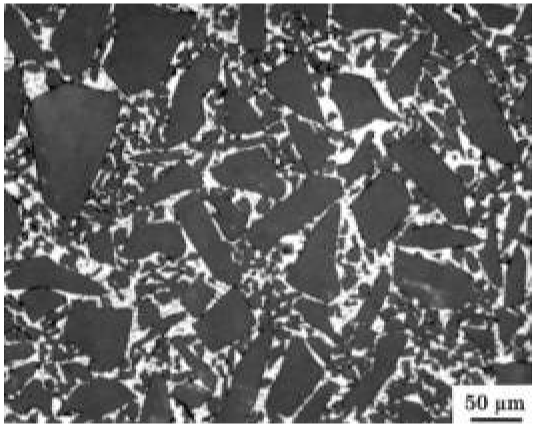
- **Process used since 1940s: AKA: reaction sintering, self bonding, melt infiltration**
- **Makes use of good wetting and highly exothermic reaction between carbon and liquid Si or Si-alloy**
- **M Cubed refined this process to achieve**
  - **Fine microstructure**
  - **Higher toughness**
  - **Near-net shape preforming technique that yields high SiC content (>70%)**
  - **Environmentally friendly**
  - **Better machinability (EDM)**
  - **Very low shrinkage(< 0.5%) from preform to infiltrated product**
  - **High strength preforms allow “green” machining to high tolerances which minimizes finish machining**
  - **Preform bonding technology allows manufacturing of complex parts**
  - **Cost-effective, large-scale manufacturing and manufacturing of large, complex components**

Metal/Ceramic Composites Offer Excellent Properties

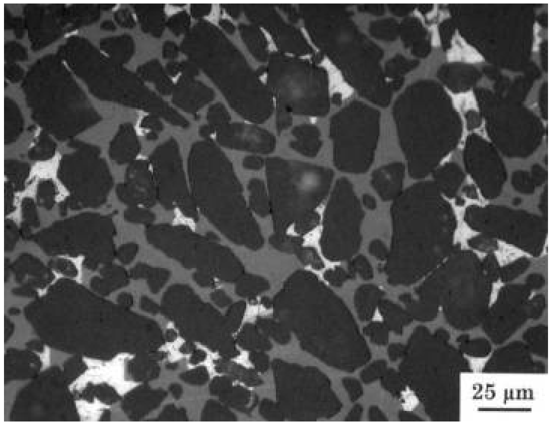
- **Reaction Bonded SiC**
  - **SSC-702 (70% SiC, 30% Si)**
  - **SSC-802 (80% SiC, 20% Si)**
- **Reaction Bonded B_4C**
  - **RBBC-751 (75% B_4C, 9% SiC, 16% Si)**
- **Reaction Bonded Hybrid Composites**
  - **HSC-701 (70%SiC, 18%Al, 12%Si)**
  - **HSC-702 (70%SiC, 12%Al, 18%Si)**
  - **HSC-703 (70%SiC, 7%Al, 23%Si)**
- **Reaction bonded C_f/SiC under development with near-zero CTE**
- **Metal Matrix Composites (MMC) – PRIMEX Process**
  - **ASC-301 (30%SiC, 70% Al) - Cast**
  - **ASC-401 (40%SiC, 60% Al) - Cast**
  - **ASC-551 (55%SiC, 45% Al) – Infiltrated**
  - **ASC701 (70%SiC, 30% Al) – Infiltrated**

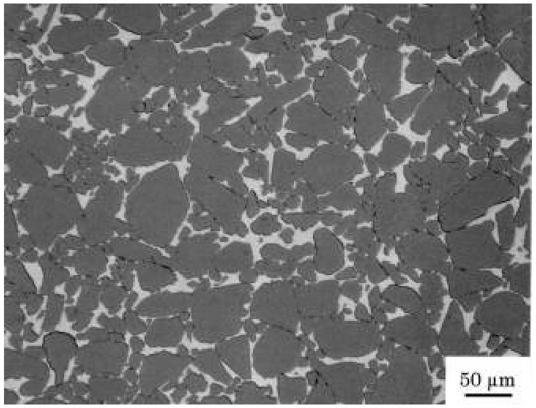
Composite Microstructures

Al/SiC-70p

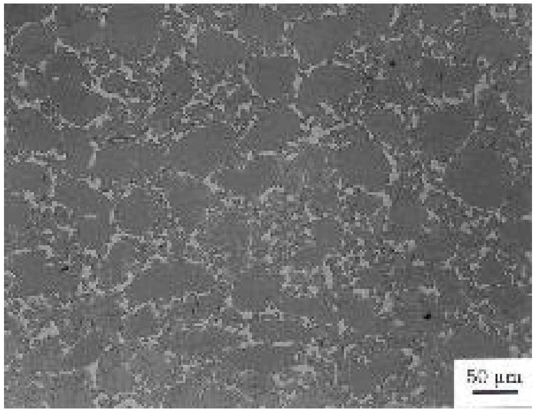


Al-Si/SiC-70p





Si/SiC-70p



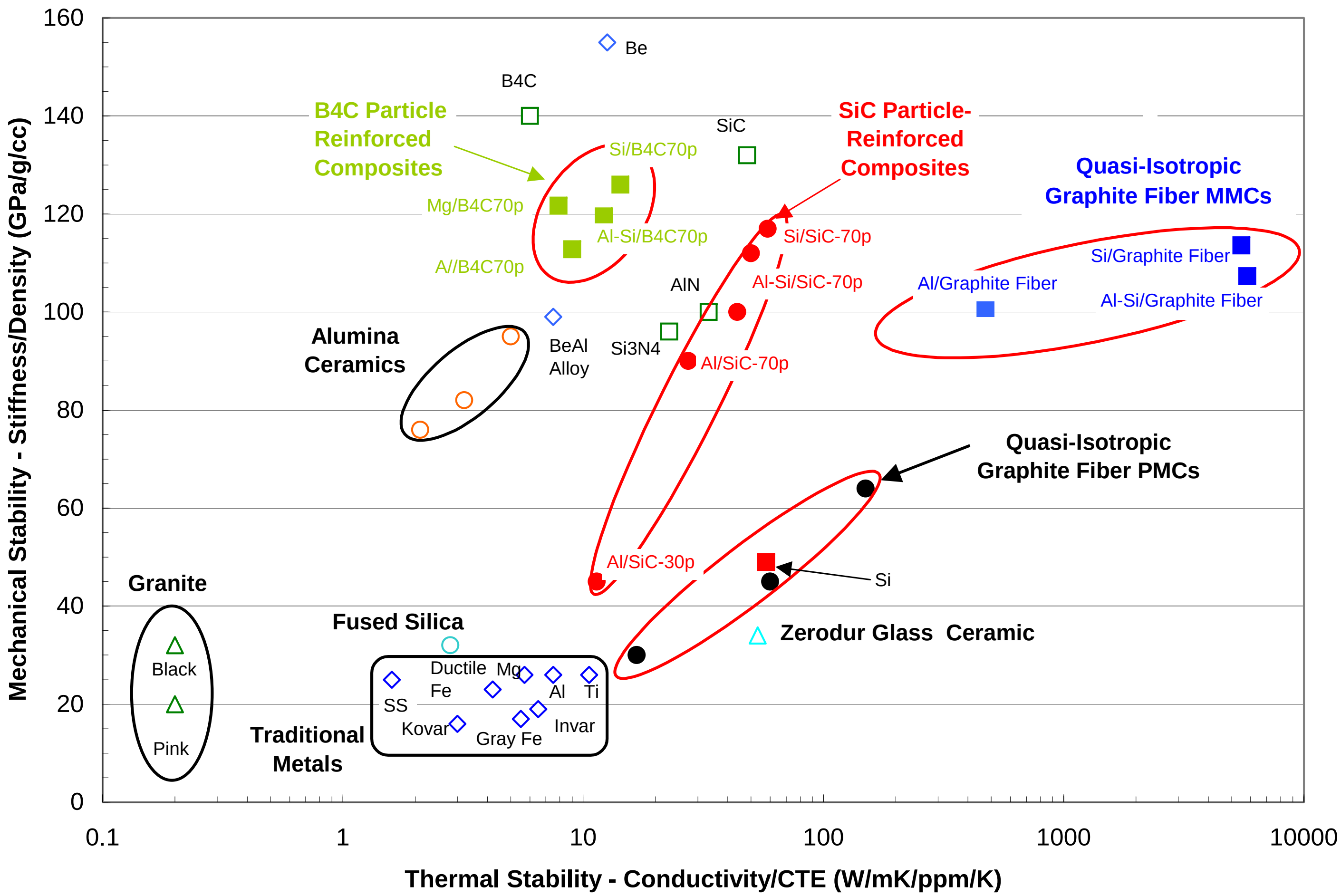
Si/B_4C-70p

Advantages of MCT's Reaction Bonding Technology for Processing SiC and B_4C-Based Materials

Process	Shape & Size Capability	Process Temp. Reactivity	Process Time	Tooling cost	Residual Porosity	Scalability	Cost
CVD	Limited	Low	Long	High	Low	Poor	High
CVI	Limited	Low	Long	High	High	Poor	High
Hot Pressing	Limited	High	Short	High	Low	Poor	High
Sintering	Good	High	Medium	High	Low	Medium	Medium
MCT Reaction Bonding	Excellent	Low	Short	Low	Low	Excellent	Low

Relative Mechanical and Thermal Stabilities of Materials

[Items circled in red are offered or under development by MCT]



Note: CTEs are average values from RT to 100°C.

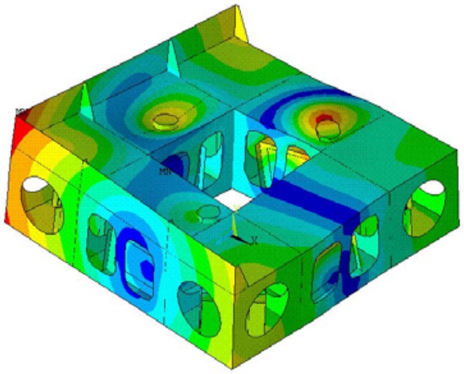
Advantages of MCT Materials and Manufacturing Processes

– MCT's materials have properties that enable solutions featuring performance enhancement and cost reduction:
  - High Specific Stiffness (High stiffness/Low Density)
  - High Thermal Stability (High Thermal Conductivity/Low CTE)
  - Good Ballistic Properties
  - Properties "tailorable" to achieve specific design results.
  - Manufacturability
    – Shrinkage < 0.5%: Near net shape manufacturing
    – Most features can be machined in "Green" state
    – High volume production (~20,000/month) of net shape cast components
    – Production of medium (0.3 m, 100s /month) and large (1 m, 10s /month) precision components

Overview of Process Steps

Precision Stage Structure

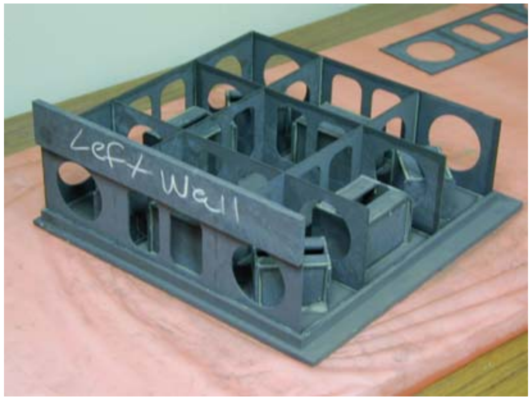
- **Major Process Steps**
  - **Design and Analysis**
  - **Mold Fabrication**
  - **Preform Fabrication**
  - **Green Machining**
  - **Preform Bonding**
  - **Infiltration**



Design/Analysis

Preform Fabrication

Green Machining



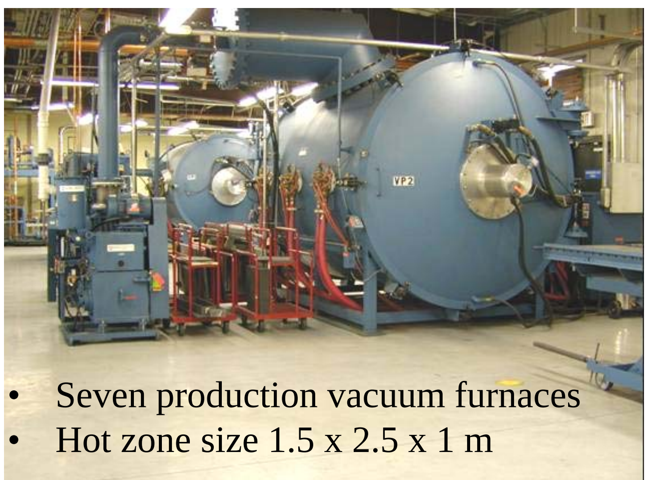
Preform Assembly/Bonding

Infiltrated Structure

Production Facilities

- Five Alternate Atmosphere Belt Kilns
- 30 m long

- Horizontal & Vertical Green Machining Centers
- Work Piece Size 2 x 0.75 x 0.75 m



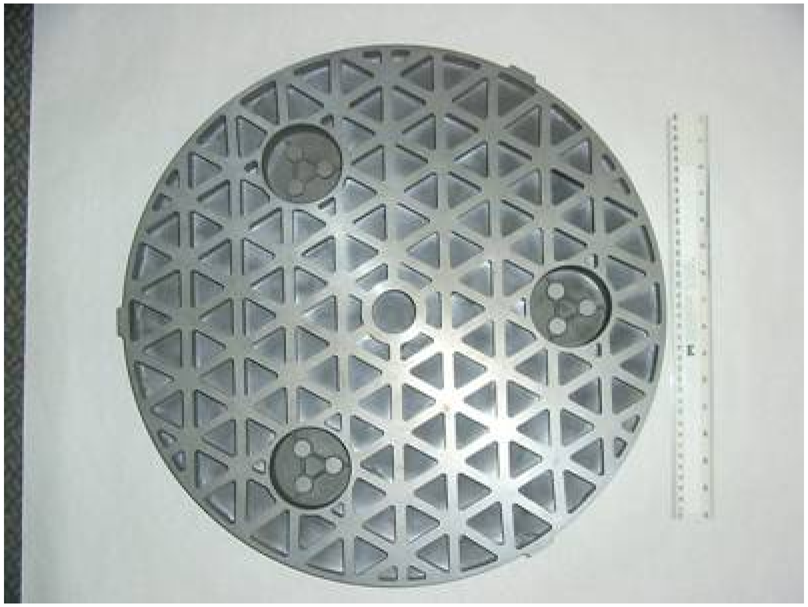
- Seven production vacuum furnaces
- Hot zone size 1.5 x 2.5 x 1 m

- Horizontal & Vertical Finish Machining Centers
- Work Piece Size 1 x 2 x 0.9 m

Reaction Bonded SiC Mirrors (Si/SiC: MCT SSC)

- 4” Polishing Blanks
- 8” Mirror Blanks
- 20” Mirror Blanks

- Light Weight
- High Resonant Frequency Design



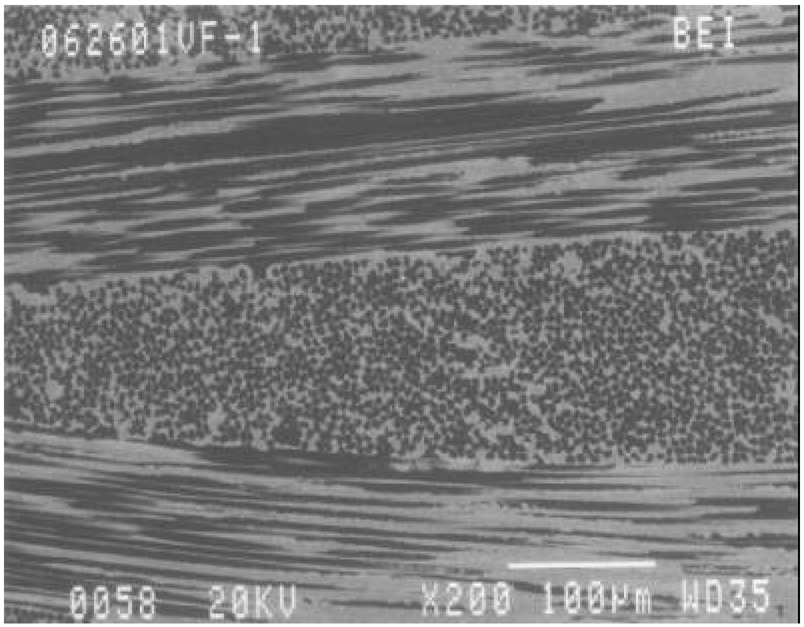
Si/SiC, Si/B_4C and C_f/SiC Mirrors

- **8 and 20 inch mirror blanks ground and lapped to ¼ wave flatness**
- **Can be easily coated and finished to high figure and finish**
- **Size Capability: 1.25 m diameter mirrors**
- **Space structures under development**
- **With C_f/SiC "zero" CTE achievable**

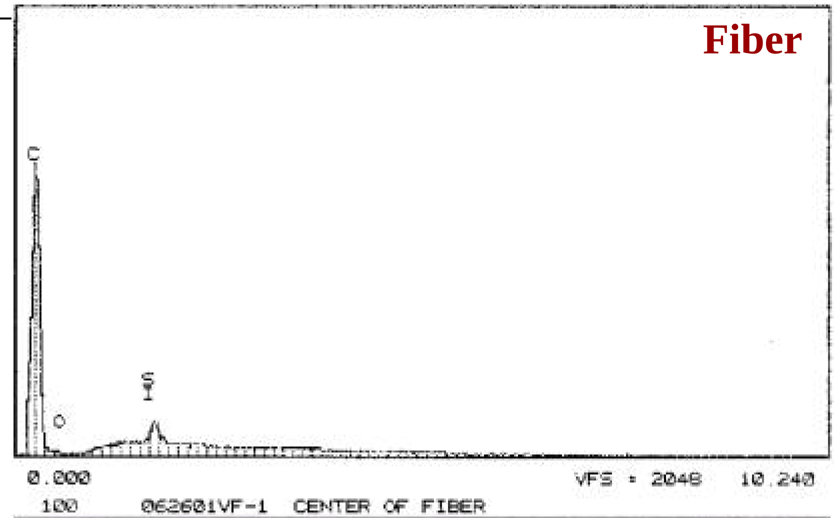
Material	Resonant Frequency (kHz)	Current Areal Density (kg/m^2)	Areal Density Easily Achievable Through Design and Manufacturing Modification (kg/m^2)*
Si/SiC	5 (Dia 8 inch) 1 (Dia. 20 inch)	17	11
Si/B_4C	N/A	14	10
C_f/SiC	0.8	12	8

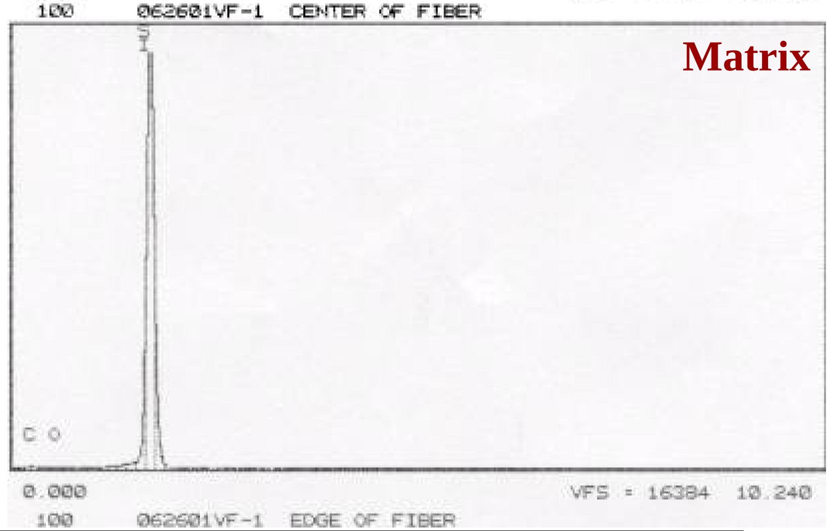
* - At a specific resonant frequency – can be lowered further if frequency is lower

Microstructure of C_f/SiC Composite



- Carbon fibers were protected successfully from molten Si during melt infiltration using low-cost, insitu-formed coatings





C_f/SiC: Properties Achieved Before Phase I

- Focus was on low to zero CTE (not mechanical properties)
- These six composites have different fiber type, architecture, interface, and processing conditions – shows ability to tailor properties

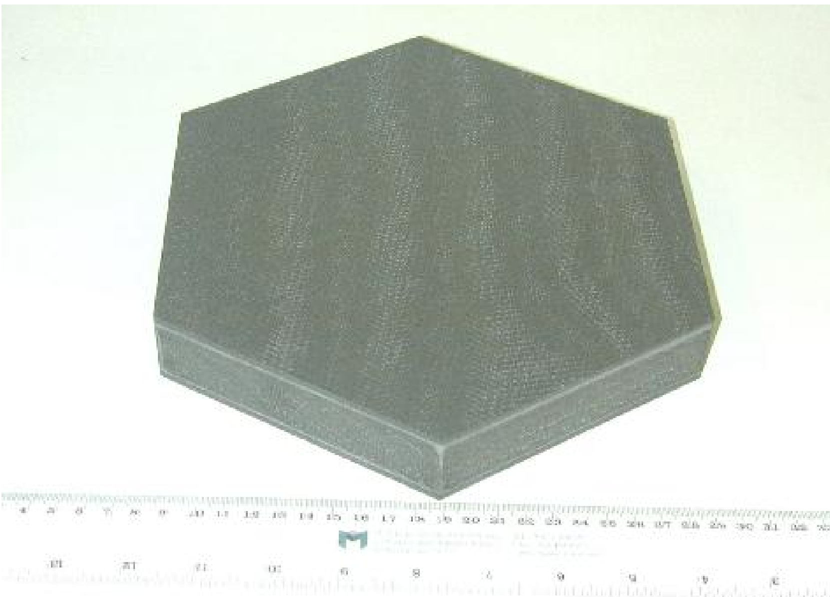
Composite	Density (g/cc)	Flexural Strength (MPa)	UTS (MPa)	Young's Modulus E (GPa)	CTE (-50 to 100°C) ppm/K	Thermal Cond. W/mK
1	2.394	64.5	32.9	154.5	0.96	68.3
2	1.995	156.0	85.5	61.3	0.77	15.5
3	2.448	108.5	--	--	1.06	91
4	2.568	183.5	--	--	1.75	143
5	2.348	126.2	--	--	1.84	94
6	2.490	162.1	107.7	112.0	-0.46	x: 114 y: 122
Invar	8.0	--	455	150	1.8	13
Zerodur	2.57	55-90	--	90	0	1.6

Mechanical Properties of C_f/SiC Composites Were Further Enhanced in the Phase I

Composite	Density (g/cc)	Flexural Strength (MPa)
A	2.221	173 +- 15
B	2.138	193 +-10
C	2.290	312 +- 20

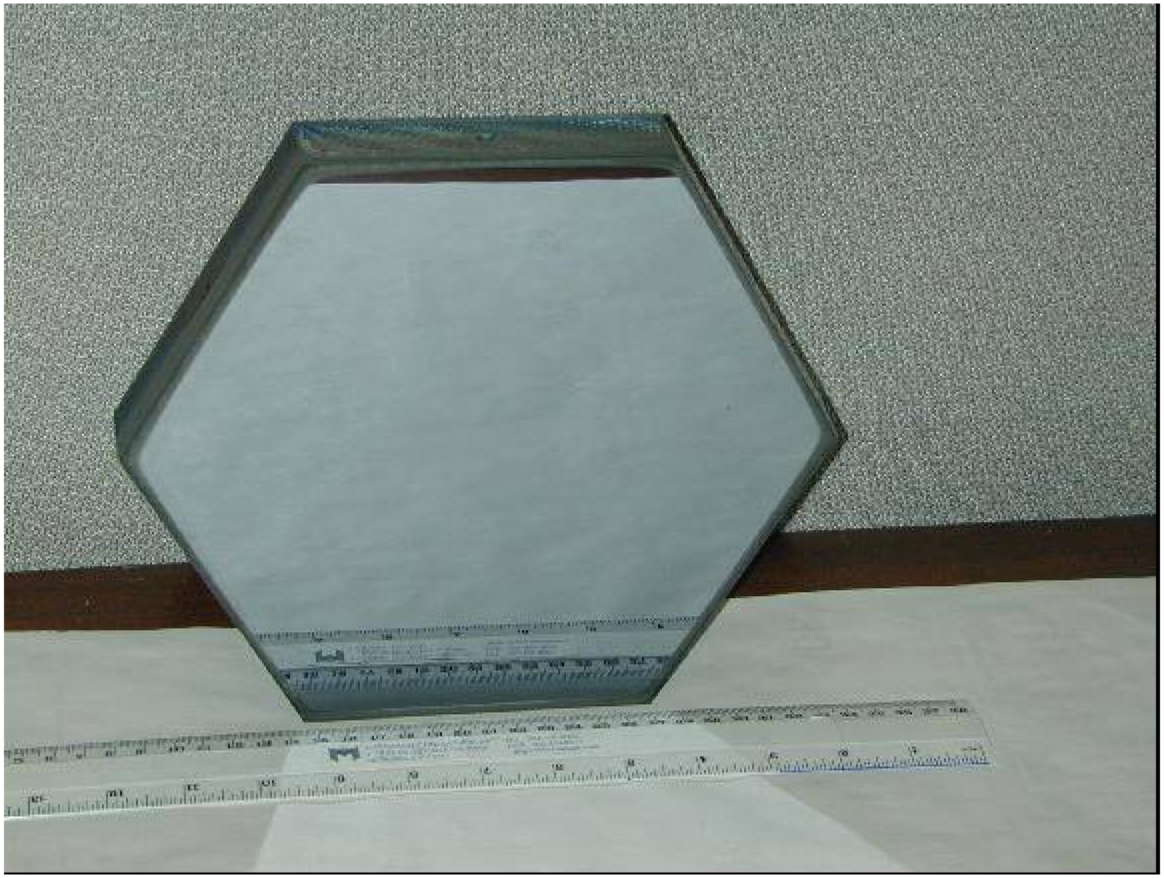
- Work continues to enhance mechanical properties even further

0.2 m C_f/SiC Hexagonal Mirror After Infiltration and Grinding



- Ribbed back and partial back cover for
  - Light weight
  - Low areal density
  - High stiffness
  - High resonant frequency

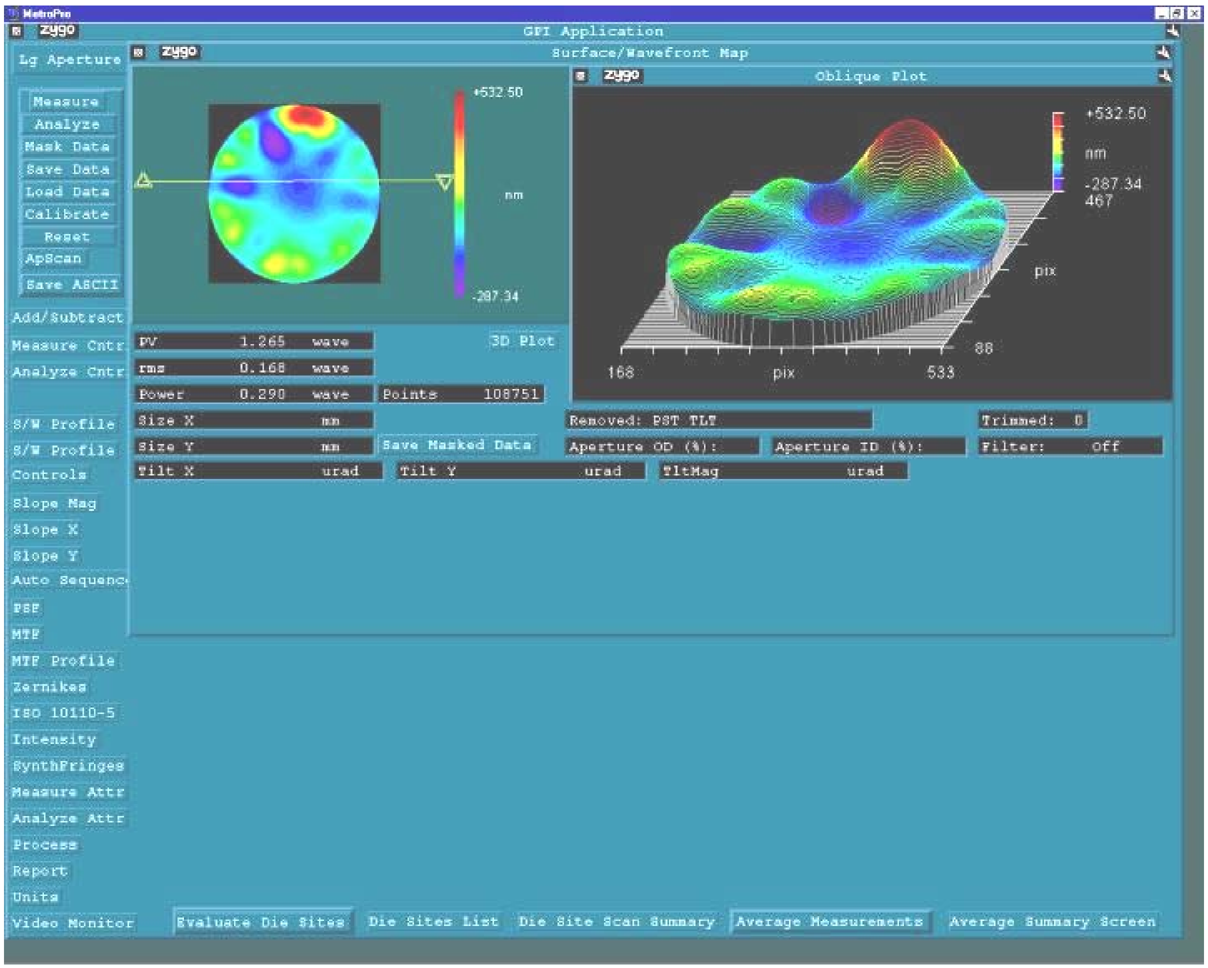
0.2 m C_f/SiC Hexagonal Mirror: Finished



This mirror was built and finished to

- **Surface Figure**
  - **0.168 wave RMS**
- **Surface Finish**
  - **3 nm Ra**
- **CTE**
  - **~1 ppm/K**

0.2 m C_f/SiC Hexagonal Mirror: Flatness After Finishing



- 0.168 Waves RMS
- 1.265 Waves PV

- Ribs “print-through” effect seen
- More ribs needed to reduce print through

A photograph of the 0.5 m Spherical Mirror After Infiltration

Infiltrated Component
(to be machined round and ground and finished)

Phase I Achievements

- During the Phase I program, C_f/SiC composite properties were further enhanced.
- Composite flexural strengths were increased by up to 59%.
- A 0.2 m hexagonal flat, light-weight, low-expansion mirror was designed, fabricated, ground, lapped, and coated.
- This mirror was finished to the following specifications:
  - Clear aperture: 7.5 inch diameter
  - Flatness: 0.168 waves rms (1.265 waves PV)
  - Average Roughness (Ra): 3 nm
- A 0.5 m spherical mirror was fabricated to demonstrate size-capability.
- Thus, the Phase I program achieved all its technical objectives and proved the feasibility of fabricating light-weight, low-expansion mirrors out of C_f/SiC composites.