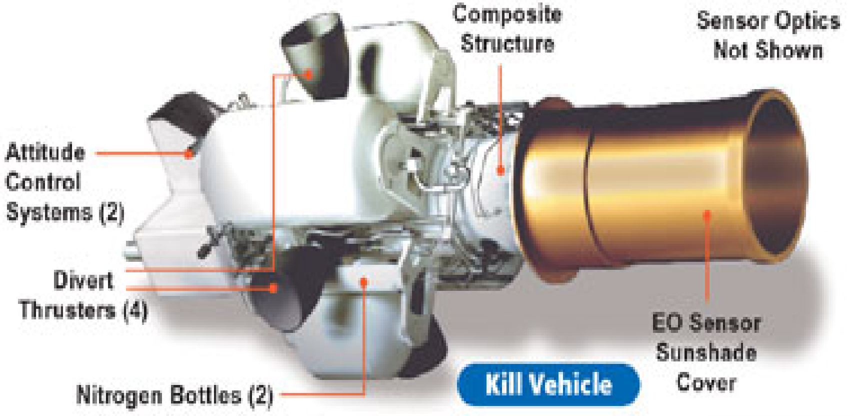

Development of Graphite Fiber Reinforced Magnesium Alloys for Lightweight Mirror Substrates and Zero CTE Metering Structures

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Metal Matrix Cast Composites, LLC

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Days, Huntsville Aug 17-19

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- **MDA Phase I contract number Contract F29601-03-M- 0280: Graphite Fiber Reinforced Magnesium as a Beryllium Replacement Material for EKV Primary Mirror"**
- **Dr. Brett deBlonk, AF Program manager**

Development of Graphite Fiber Reinforced Magnesium Alloys for Lightweight Mirror Substrates and Zero CTE Metering Structures:
Outline

- Why Magnesium?
- Why Mg/Gr?
- Continuous Mg/Gr Composites
- Discontinuous Mg/Gr Composites
- Calculated and measured properties
- Applications and Manufacturing Methods
  - Mirrors- Discontinuous fiber preforms
  - Optical bench, metering structures
- Conclusions

Why Magnesium?

- Low density: AZ31 alloy: 1.85 g/cc
  (AZ31= Mg 3Al-1Zn)
- Same specific stiffness as Al, Ti, Fe
- Compatible with high performance graphite fibers
- Electrically conductive
- High thermal conductivity
- No outgassing in space and orbital environments

Why Mg/Gr Composites?

- Low density ~2 g/cc
- Higher stiffness than Be >70 msi
- Higher specific stiffness than Be ~1.5x
- Low CTE/high thermal stability
- Potentially lower mass structures than Be
- Low cost
- Matrix is ductile···No crazing or microcracking
- Non-toxic

Constituent Materials

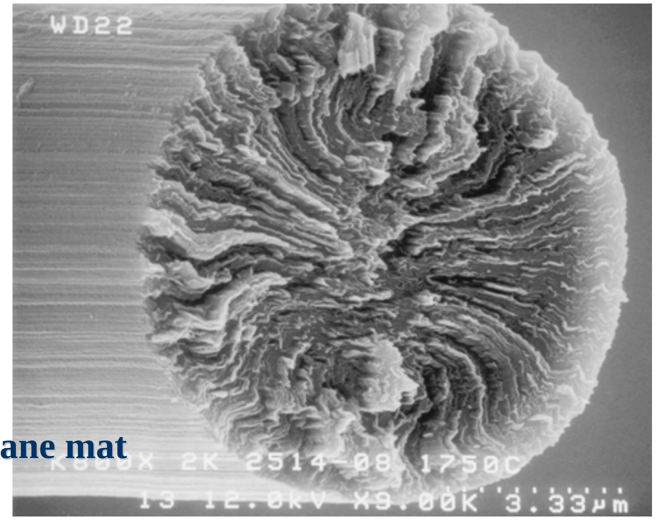
Matrix Alloys	Composition	E (gPa)	CTE (ppm/K)	TC (W/mK)
Mg- AZ-31	Mg- 3 Al- 0.2 Mn- 1 Zn	45 “	26	96
Mg-AZ-91D	Mg- 9 Al- .13 Mn- 1 Zn	45 (6.5 msi)	26	72
Mg- ZC-61	Mg- 6 Zn- 3 Cu- 0.5 Mn	45 “	26	122
Al 413-HP	Al-12.5 Si- 0.3Mg	71 “	21	167

Graphite Fiber Reinforcement

	E_1 gPa (msi)	E_2 gPa (msi)	CTE ppm/K	TC-W/mK
*CKD-x:	862 (125)	6.9 (1)	-1.5	550
*CKA-x:	965 (140)	6.9 (1)	-1.5	950
**K63B12	862 (125)	6.9 (1)	-1.5	440
**K63712	641 (93)	6.9 (1)	~1.5	140

*Cytec graphite fibers: 1” chopped, processed into a random, in plane mat

**Mitsubishi continuous fibers

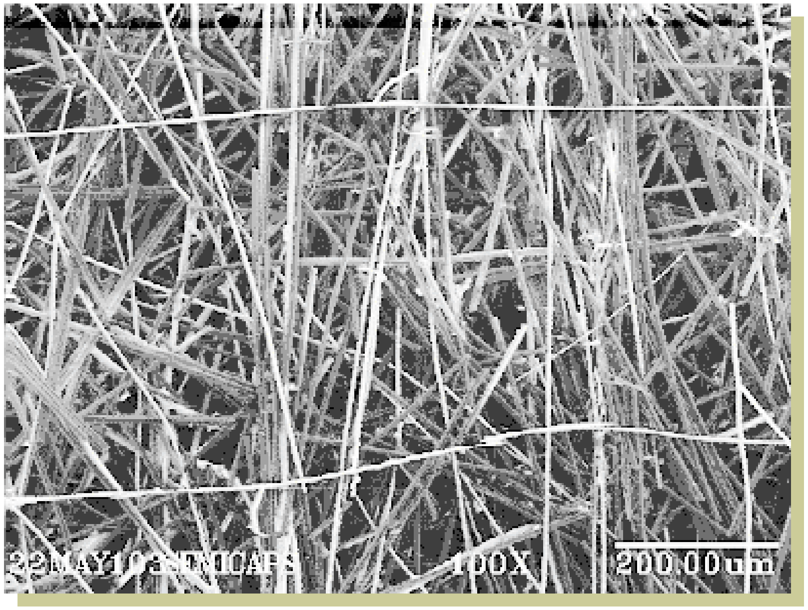


Discontinuous Reinforced Composites

- Low cost
- Continuous control of volume fraction reinforcement
- Easy to machine into mirror substrates or electronic thermal management packages
- Near quasi-isotropic properties

Modified Schapery's Equation for Composite CTE Prediction

$$\alpha_{cx} = \frac{\alpha_m E_m v_m + \alpha_{fa} E_{fa} \frac{v_f}{2} + \alpha_{ft} E_{ft} \frac{v_f}{2}}{E_m v_m + E_{fa} \frac{v_f}{2} + E_{ft} \frac{v_{ft}}{2}}$$



Where:

α_{cx} = coefficient of thermal expansion of composite

E = Young's modulus of elasticity

v = volume fraction reinforcement

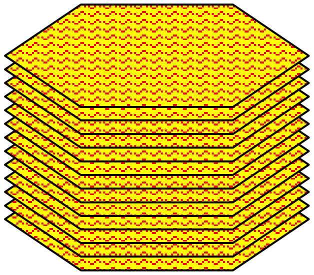
Subscripts:

m = matrix

f = fiber

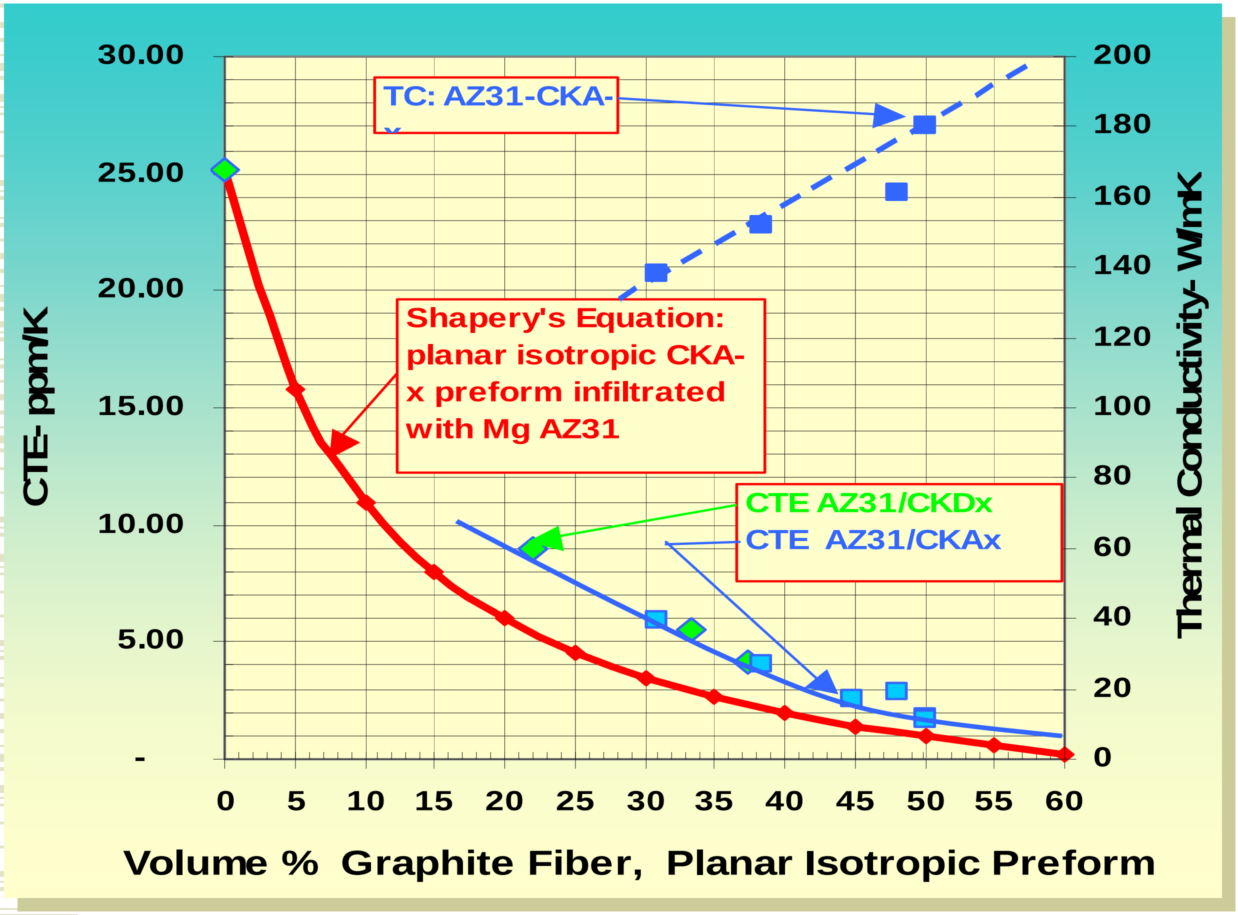
fa = fiber axial

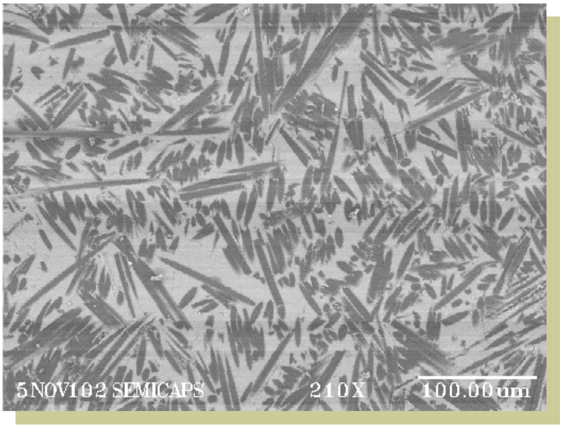
ft = fiber transverse



Planar-isotropic architecture results from discontinuous fibers randomly distributed in-plane

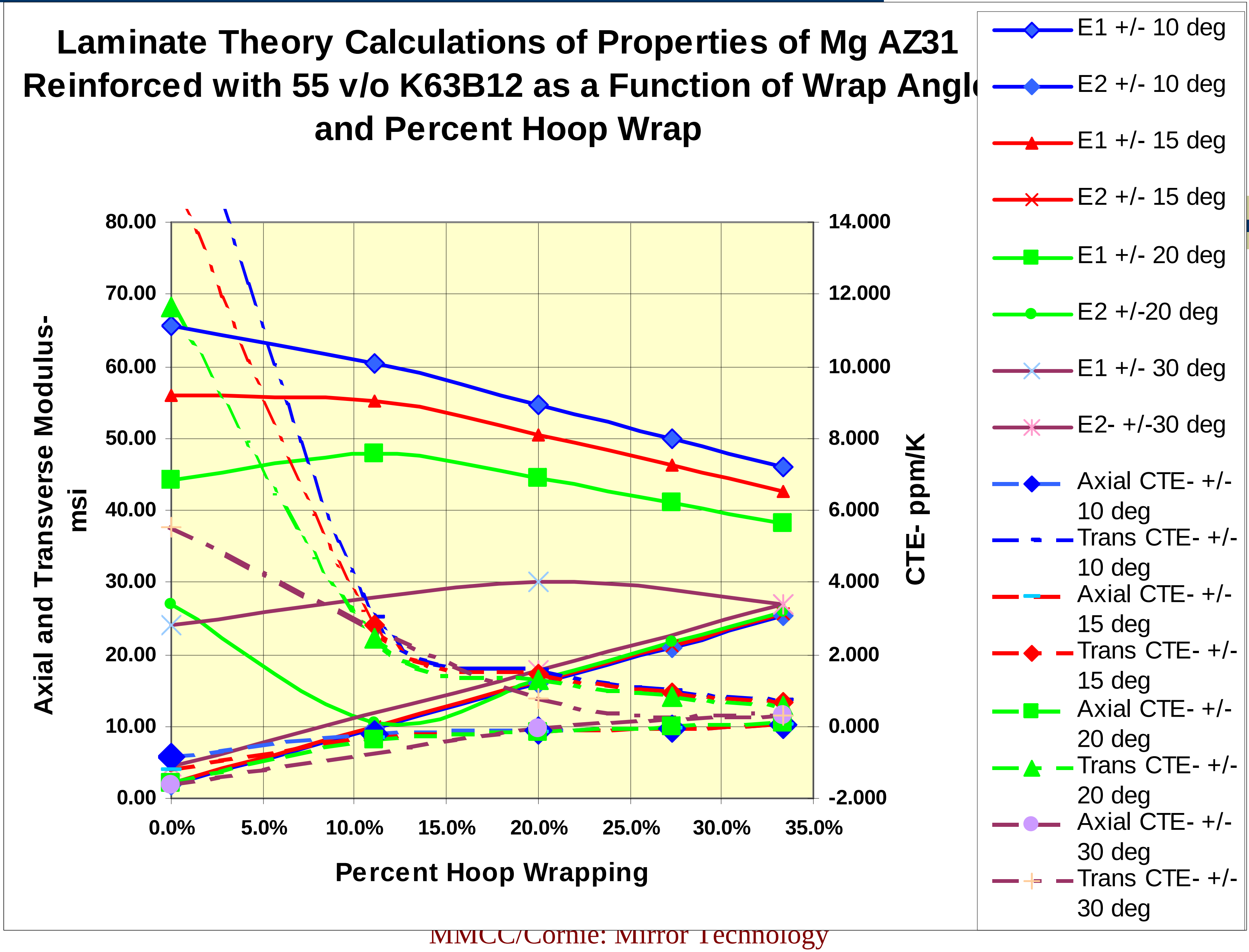
Variation of CTE (and Thermal Conductivity) with v/o Compared to Shapery's Equation (and Rule of Mixtures Calculations)

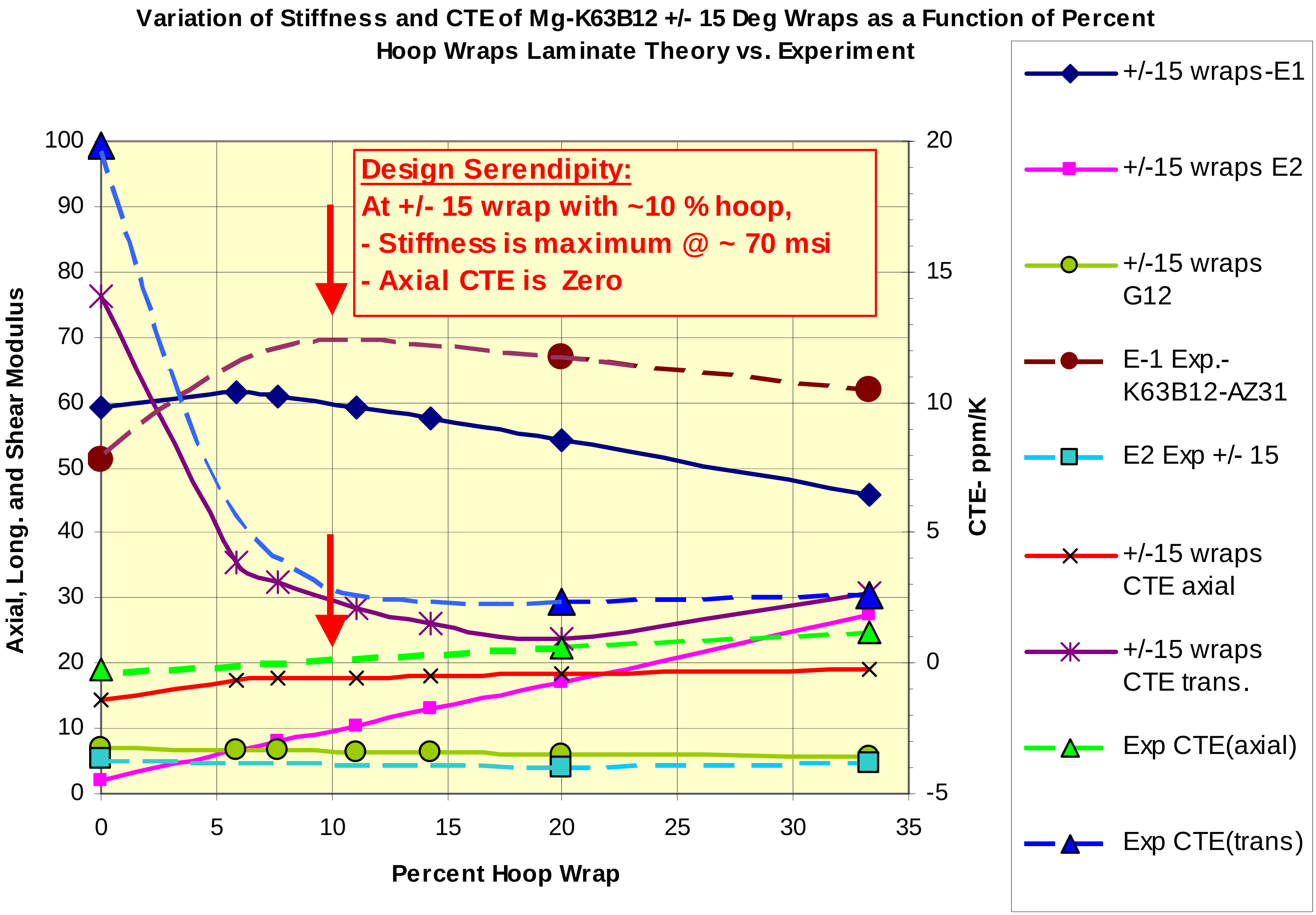




Continuously Reinforced Angle-Ply Graphite/Mg Composites

- High stiffness
- Low density
- High strength
- Low CTE in axial and transverse directions
- Zero CTE in axial direction easy to achieve
- Higher specific stiffness than Be
- Non toxic
- Lower Cost than Be
- Electrically conductive/High CTE


Laminate Theory Calculations of Properties of Mg AZ31 Reinforced with 55 v/o K63B12 as a Function of Wrap Angl and Percent Hoop Wrap
Axial and Transverse Modulus- msi
CTE- ppm/K
Percent Hoop Wrapping
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
-2.000
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
30.0%
35.0%
E1 +/- 10 deg
E2 +/- 10 deg
E1 +/- 15 deg
E2 +/- 15 deg
E1 +/- 20 deg
E2 +/-20 deg
E1 +/- 30 deg
E2- +/-30 deg
Axial CTE- +/- 10 deg
Trans CTE- +/- 10 deg
Axial CTE- +/- 15 deg
Trans CTE- +/- 15 deg
Axial CTE- +/- 20 deg
Trans CTE- +/- 20 deg
Axial CTE- +/- 30 deg
Trans CTE- +/- 30 deg



Variation of Stiffness and CTE of Mg-K63B12 +/- 15 Deg Wraps as a Function of Percent Hoop Wraps Laminate Theory vs. Experiment

Design Serendipity:

At +/- 15 wrap with ~10 % hoop,

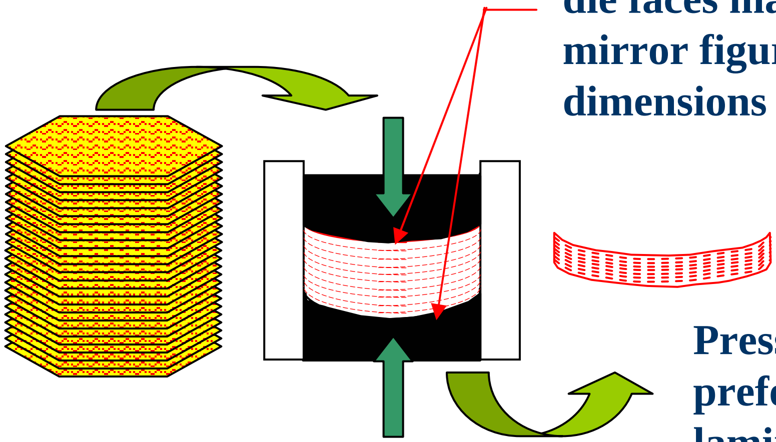
- Stiffness is maximum @ ~ 70 msi

- Axial CTE is Zero

Fabrication of Continuous and Discontinuously Reinforced Mg/Gr Composite Structures

- 1) Discontinuously Reinforced Composites:
  - Randomly dispersed in-plane paper-like preform
  - Compress with binder to desired v/o
  - Set binder and load into confining mold
  - Debinder in mold, pressure infiltration cast with Mg and directional solidify for porosity free composite.

Discontinuous or Continuous Angle Ply Graphite, (or Hybridized) Fiber Preform Manufacture



Convex and concave die faces machined to mirror figure dimensions

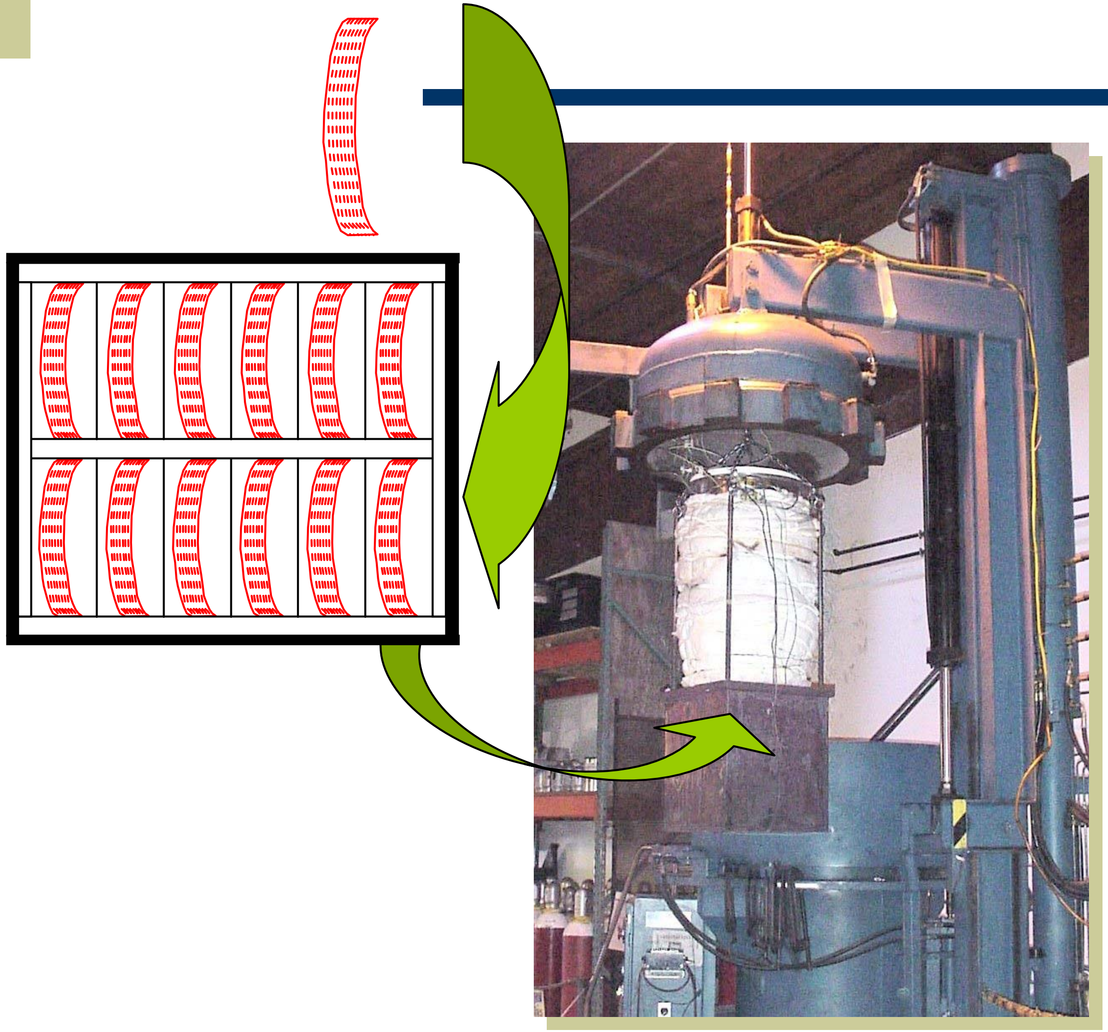
Pressed and stabilized preform with original laminates parallel to mirror figure surface

Preforms composed of

- **Paper mats of random-in-plane lamina or**
- **Quasi-isotropic angle ply laminates hybridized with paper mats**

Press to desired v/o fiber, heat to melt binder, then chill to set fugitive binder

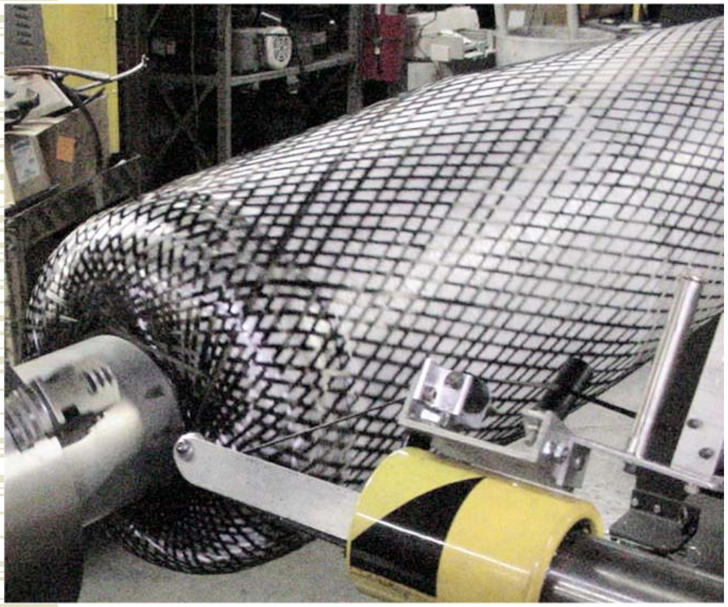
APIC^{tm} Facility



Fabrication of Continuous and Discontinuously Reinforced Mg/Gr Composite Structures at MMCC

- 2) Continuously Reinforced Composites
  - Filament wind to desired ply pattern
  - Remove from winding mandrel for panel preform
  - Leave on winding mandrel for tubular structures
  - Load into casting mold, debinder and pressure infiltrate with molten Mg, directionally solidify for porosity free casting.

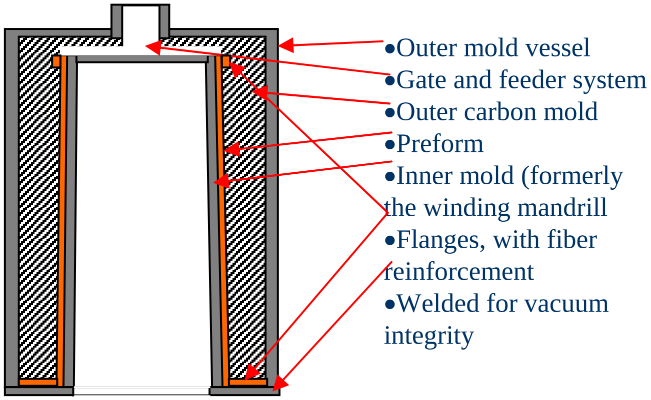
Tubular Structures Manufacturing Steps:



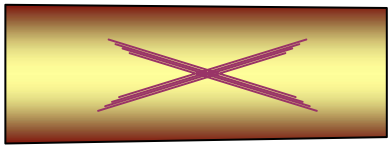
- Manufacture steel wrapping mandrel/casting core to ID dimensions (compensated for thermal contraction
- Fit with end plugs and attach to shaft

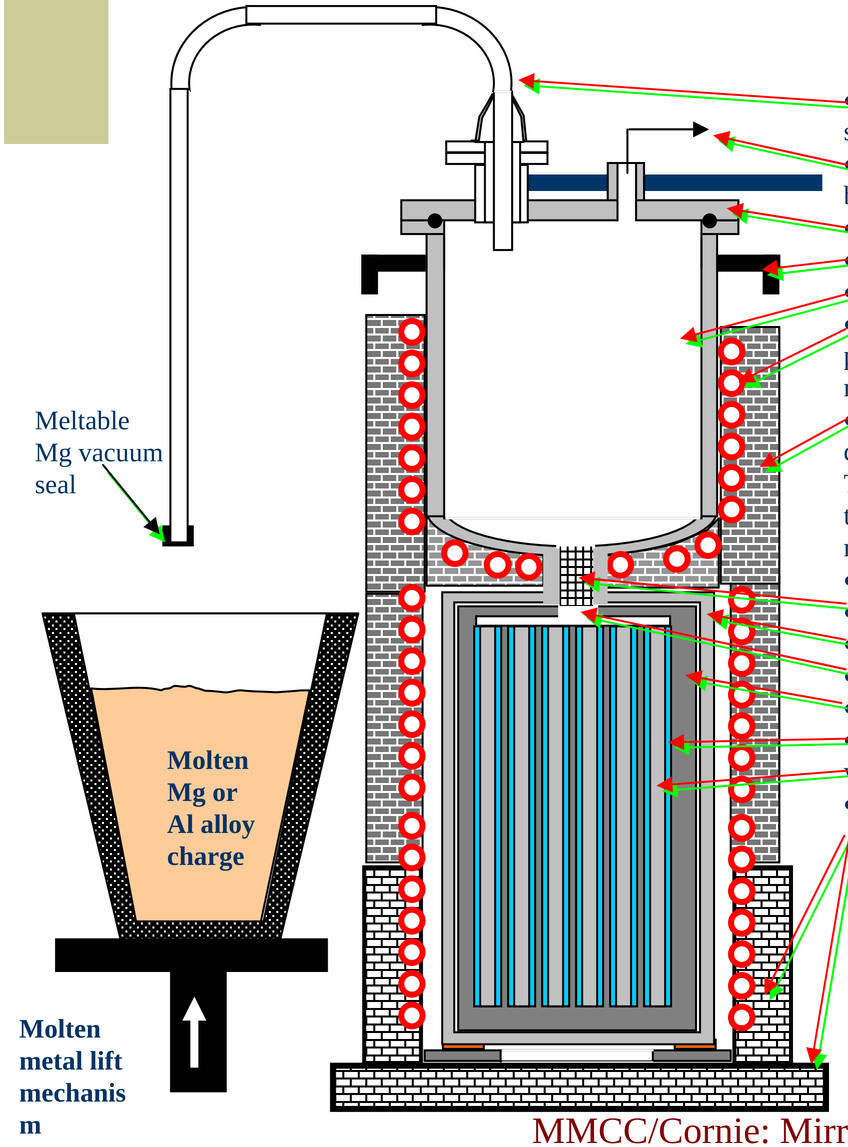
- Wrap mandrel with Saffil or chopped glass paper

- Wind with desired angle and hoop architecture with fugitive binder



- Outer mold vessel
- Gate and feeder system
- Outer carbon mold
- Preform
- Inner mold (formerly the winding mandrill
- Flanges, with fiber reinforcement
- Welded for vacuum integrity





- Vacuum melt transfer system
- To vacuum pump or binder condenser
- Removable vacuum lid
- Lifting hooks
- Molten metal reservoir
- Heating coils for preheating molten metal reservoir
- Insulation to insure directional solidification- This insulation is attached to the mold and melt reservoir.
- Dross filter
- Outer mold vessel
- Gate and feeder system
- Outer carbon mold
- Preforms
- Cores (formerly the winding mandrel
- Base plate insulation

Optical Bench/ Metering Structures

- Filament wound Mg-Gr can be designed to Zero thermal expansion in axial direction with transverse CTE ~2 ppm/K
- Specific Stiffness 1.5 x Be and 9.5 x Invar
- Egg crate designs are possible with filament wound preforms sliced from the mandrel and laid out flat and cast as panels which are subsequently cut into egg crate patterns

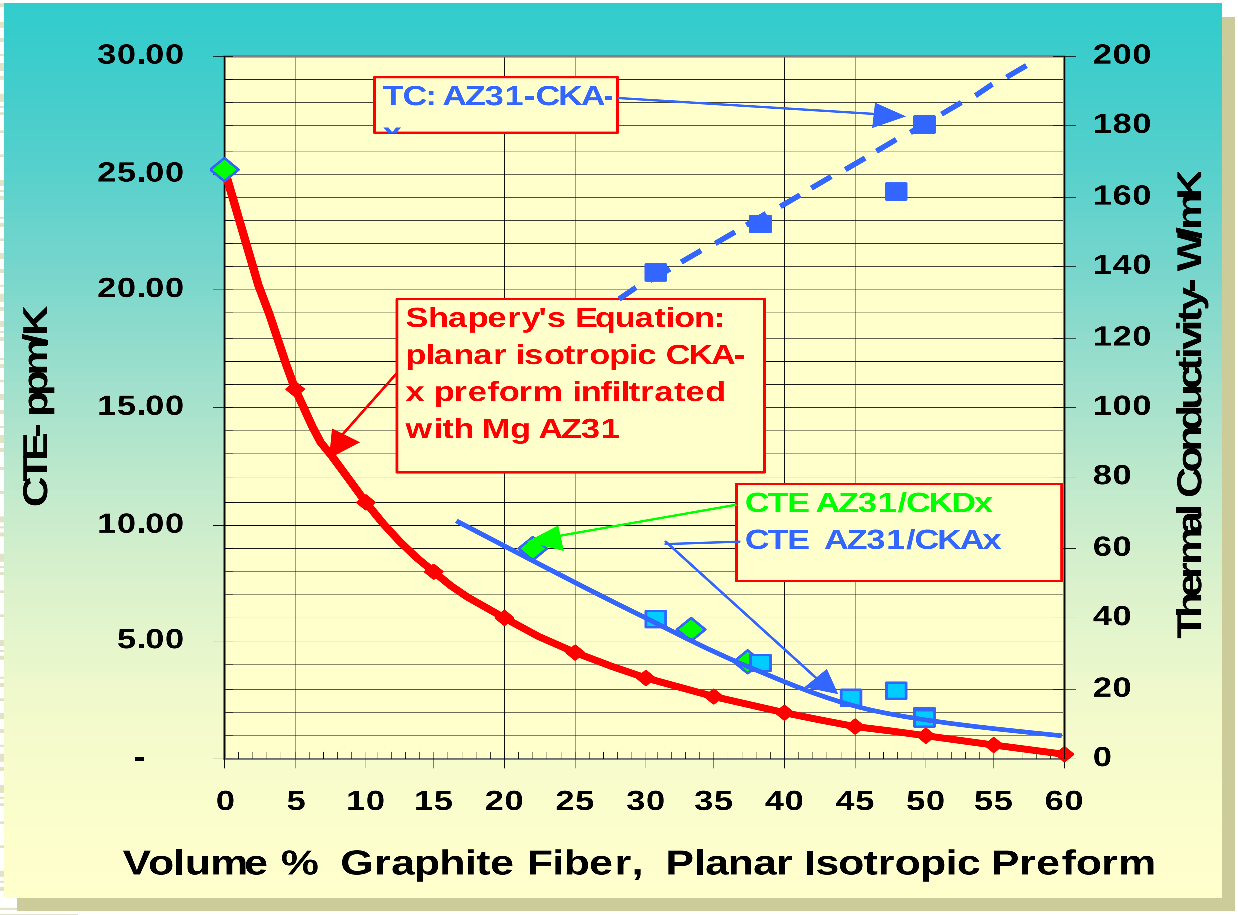
Metering Structures: Summary

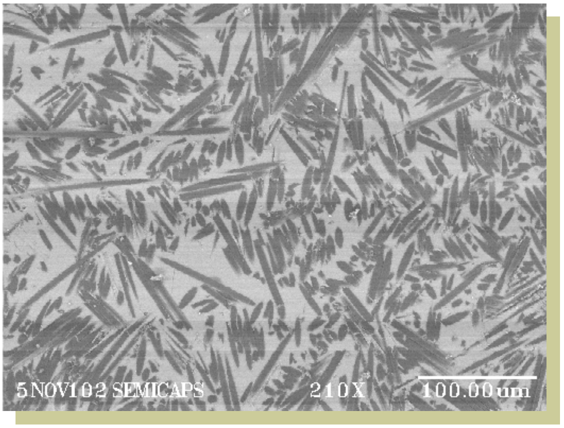
- Planar isotropic CTE ~1 ppm produced for MetGraf Mg mirror substructures. CTE can be specified and controlled by varying volume fraction reinforcement.
- Structures can be filament wound to produce a specific stiffness ~1.5 x Be and CTE = zero
- Fabrication technology for Mg/Gr is mature and robust

Lightweight Mirror Development

- CVD design to match the reflective membrane
- Comparative specific stiffness and thermal stability of candidate mirror and membrane materials
- Dimensional stability after thermal cycling
- Thermal seasoning
- CTE matching to Si and SiC membranes
- Membrane attachment and lightweight machining

Variation of CTE (and Thermal Conductivity) with v/o Compared to Shapery’s Equation (and Rule of Mixtures Calculations)

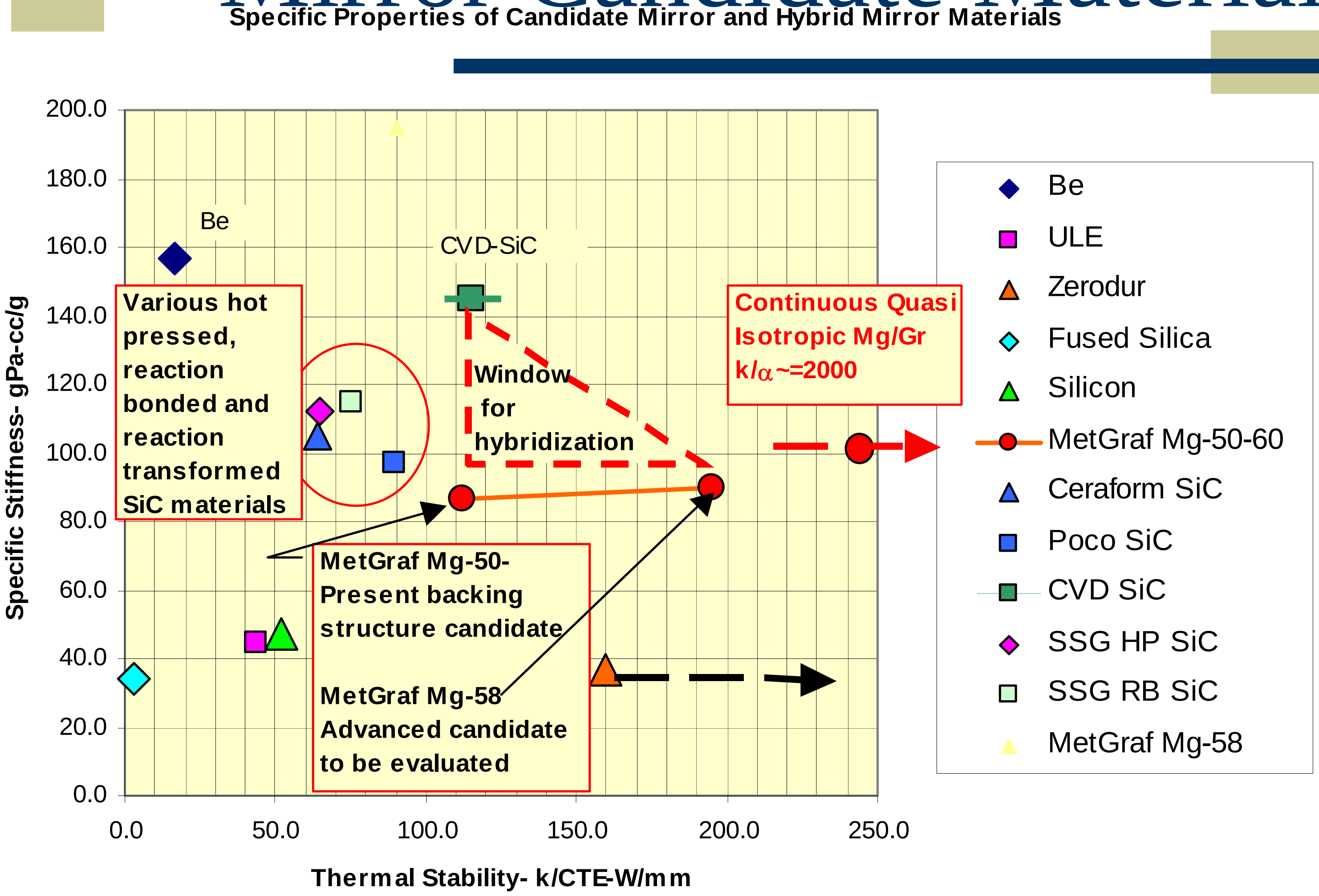




Properties of Candidate Space Mirror Materials

Material \ Property	**Modulus E-gPa**	**density g/cc**	**Specific Stiffness gPa-cc/g**	**CTE ppm/K**	**Thermal Cond. W/mK**	**Thermal Stability K/CTE- W/mm**	**Reference**
Mg	44.8	1.77	25.3	26	122	4.7	ASM Metals Hbk
Be	289.6	1.85	156.5	11.6	190	16.4	"
Al	69.0	2.70	25.5	22.7	170	7.5	"
ULE	98.0	2.21	44.3	0.03	1.31	43.7	Xinetics- NMSFC workshop 5/01
Zerodur	92.0	2.50	36.8	0.01	1.6	160.0	Poco- NMSFC workshop 5/01
Fused Silica	72.0	2.10	34.3	0.5	1.5	3.0	Poco- NMSFC workshop 5/01
Silicon	110.0	2.33	47.2	2.4	125	52.1	ASM Metals Hbk
Gr/Mg P-I Phase I	**172.0**	**1.98**	**86.9**	**1.67**	**180**	**107.8**	**MMCC Ph. I**
Gr/Al Phase I	**180.0**	**2.38**	**75.6**	**1.5**	**220**	**146.7**	**MMCC Ph. I**
Ceraform SiC	310.0	2.95	105.1	2.44	156	63.9	Xinetics- NMSFC workshop 5/01
Poco SiC	248.0	2.55	97.3	1.9	170	89.5	Poco- NMSFC workshop 5/01
CVD SiC	448.0	3.21	139.6	2.6	240	92.3	
SSG HP SiC			112.0			65.0	SSG- NMSFC workshop 5/01
SSG RB SiC			115.0			75.0	"
Mg/Gr Quasi Isotropi	**203.0**	**2.00**	**101.6**	**0.45**	***200***	**444.4**	JC Lam. Theory + ROM for K
Gr/Al Quasi isotropic	**210.0**	**2.37**	**88.6**	**1.14**	***220***	**193.0**	"

Performance Comparison for Mirror Candidate Materials



Various hot pressed, reaction bonded and reaction transformed SiC materials

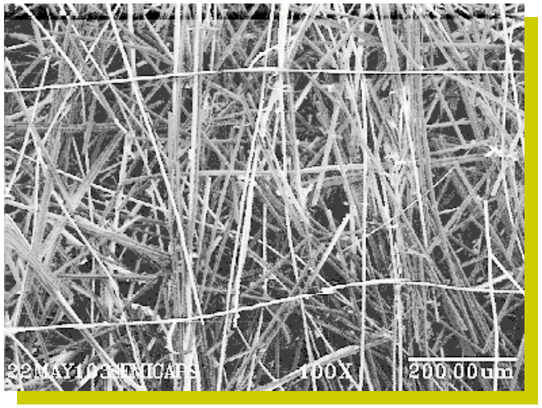
Window for hybridization

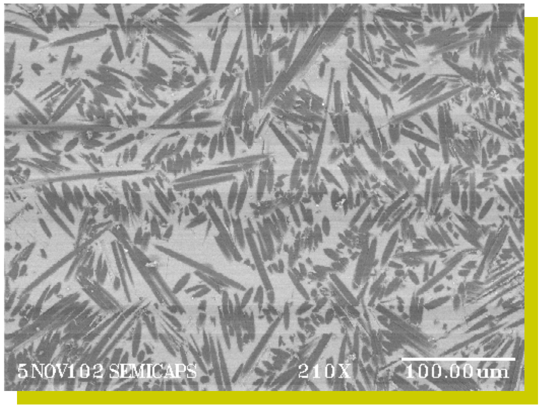
Continuous Quasi Isotropic Mg/Gr k/α~=2000

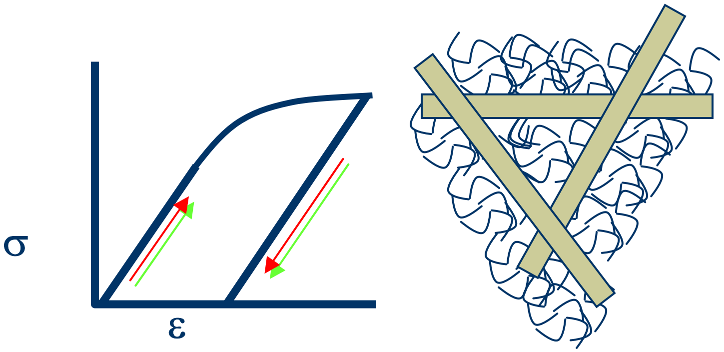
MetGraf Mg-50- Present backing structure candidate

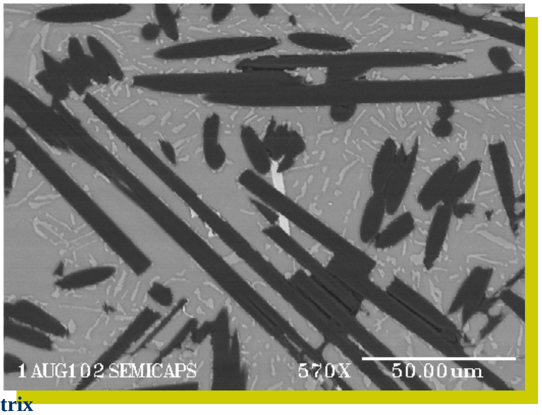
MetGraf Mg-58 Advanced candidate to be evaluated

Cold working: Proposed method of producing dimensional stability



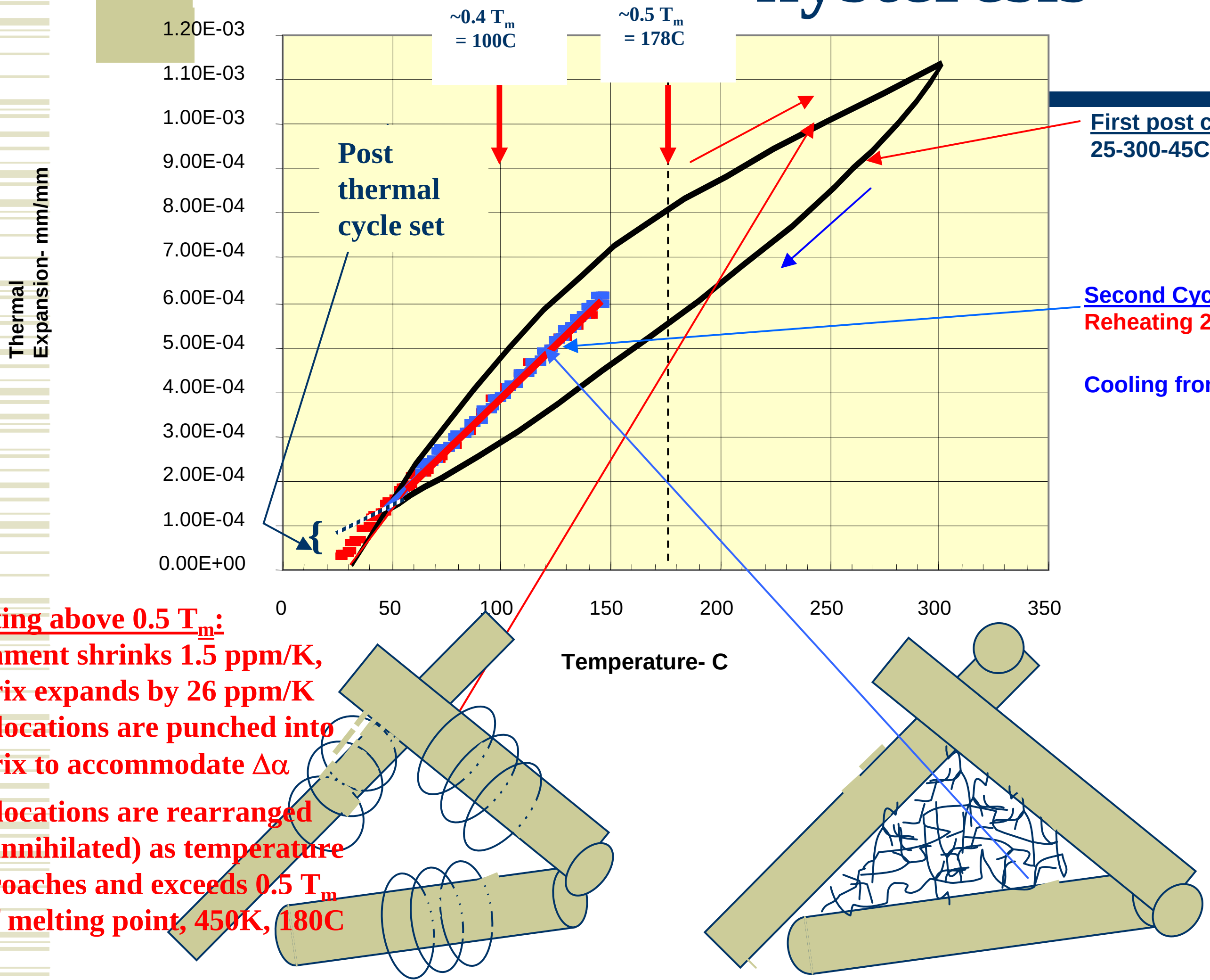






Straining composite to beyond micro-yield leads to work hardening of matrix by creating dislocations

Illustration that differential expansion induced cold work can eliminate hysteresis



First post cast cycle:
25-300-45C

Second Cycle:
Reheating 25 C to 145C-

Cooling from 145C to 40C

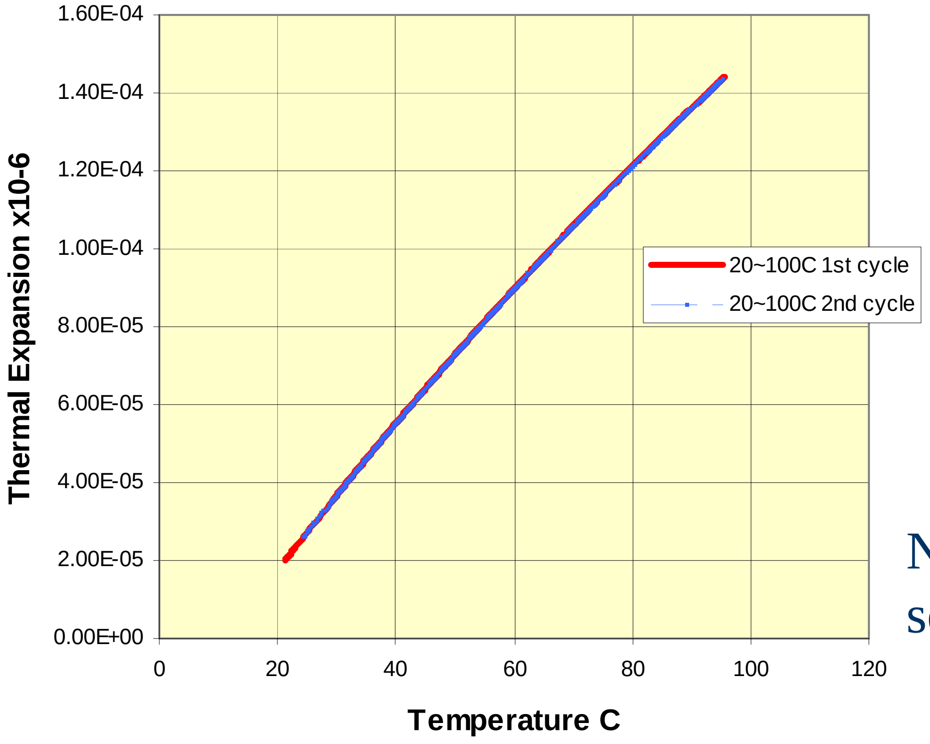
Heating above 0.5 T_m:

- Filament shrinks 1.5 ppm/K, matrix expands by 26 ppm/K
- Dislocations are punched into matrix to accommodate $\Delta\alpha$
- Dislocations are rearranged (or annihilated) as temperature approaches and exceeds 0.5 T_m (half melting point, 450K, 180C

Cooling below 0.5T_m and thermal cycling below 0.5 T_m.:

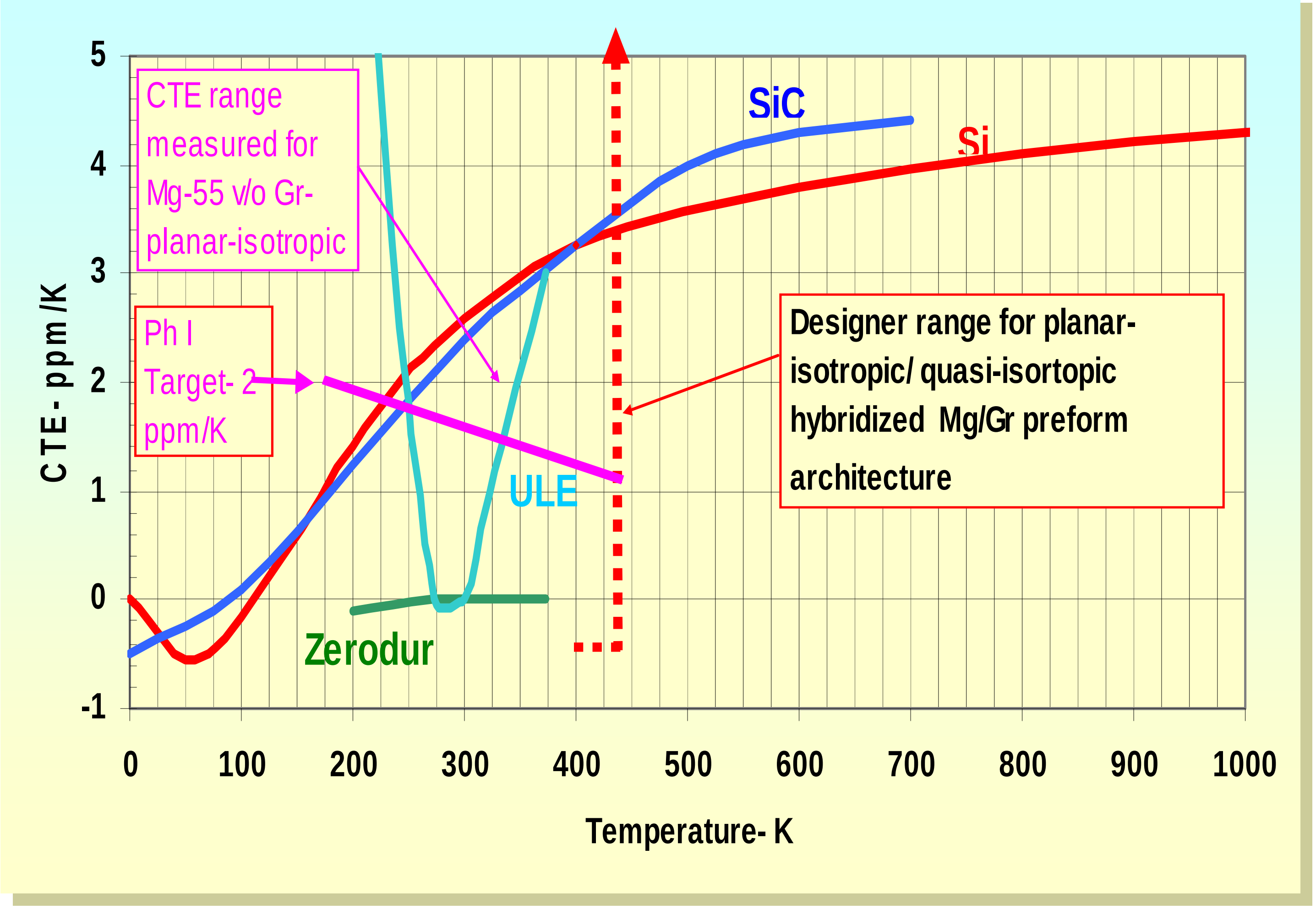
- Filament expands 1.5 ppm/K, matrix shrinks 26 ppm/K
- Dislocations are punched to accommodate $\Delta\ \alpha$ of 27.5 ppm/K
- Dislocations are created faster than they are annihilated as temperature decreases below 0.5 T_m, leading to work hardening matrix
- Further thermal cycling below 0.5 T_m will rearrange dislocations into a stable substructure
- No distortions or “set” after repeated thermal cycling at application temperatures

Two thermal expansion cycles of MetGraf Mg 50 after two thermal seasoning cycles from RT ➔125C➔-75C ➔ RT.



Note lack of thermal set or hysteresis.

CTE of Silicon and SiC As a Function of Temperature



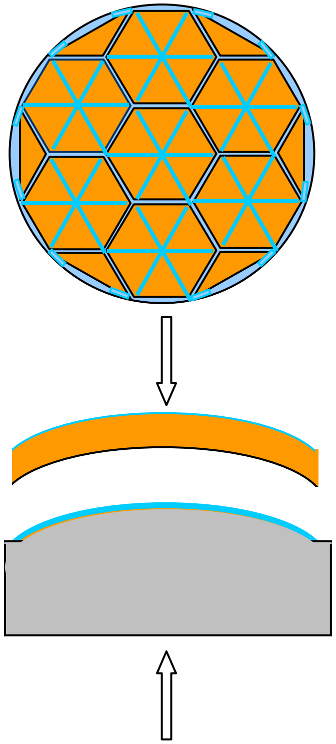
CTE range measured for Mg-55 v/o Gr-planar-isotropic

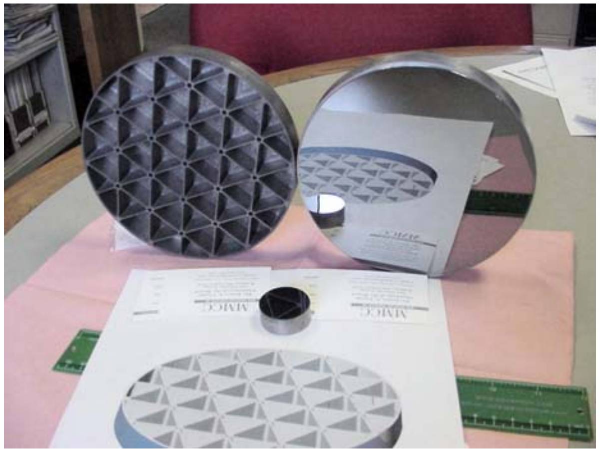
Ph I Target- 2 ppm/K

Designer range for planar-isotropic/ quasi-isortopic hybridized Mg/Gr preform architecture

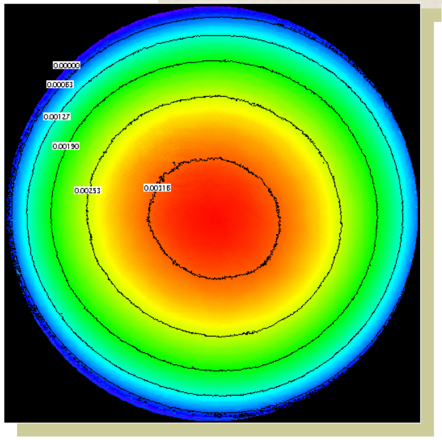
Three Approaches to Lightweight Low-Cost Mirrors

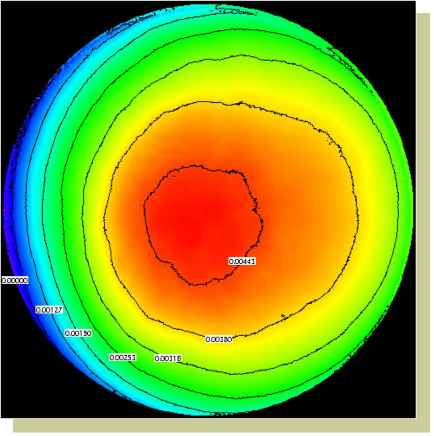
1) **Si coat Metgraf-Mg, then polish**
2) **Replicate on master (nanolaminate or polymer) and transfer to MetGraf Mg**
3) **Adhesive or solder bond surface membrane of Si or SiC and polish**



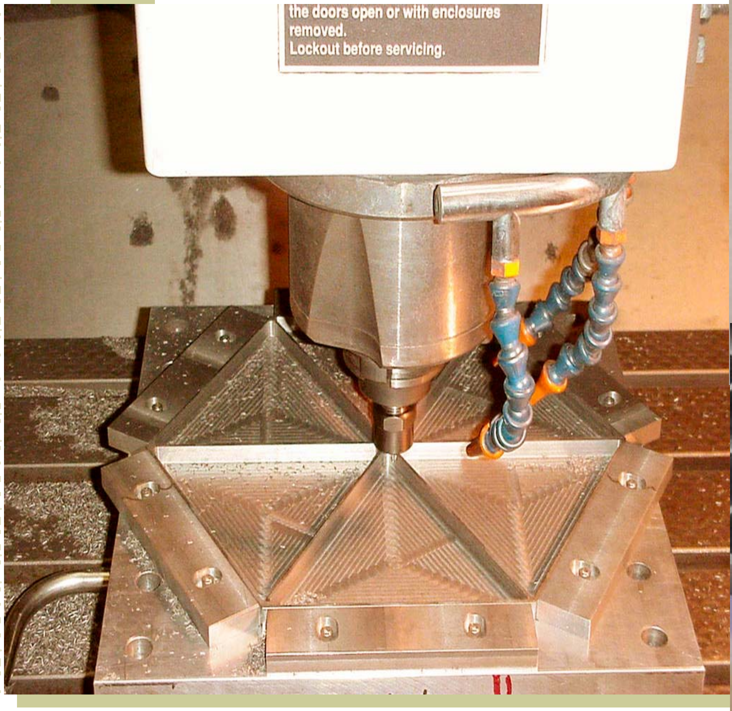


Polished Si Coated MetGraf Al and Mg





Lightweighting and Hybridizing SiC with MetGraf Mg



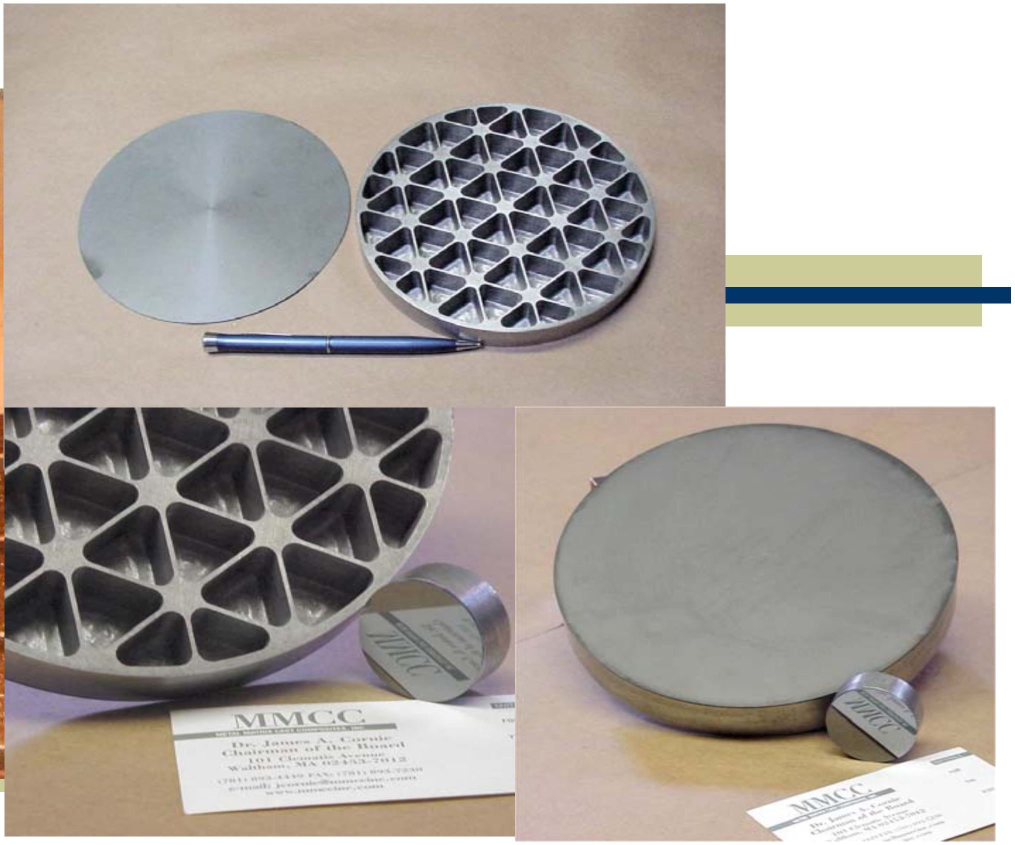


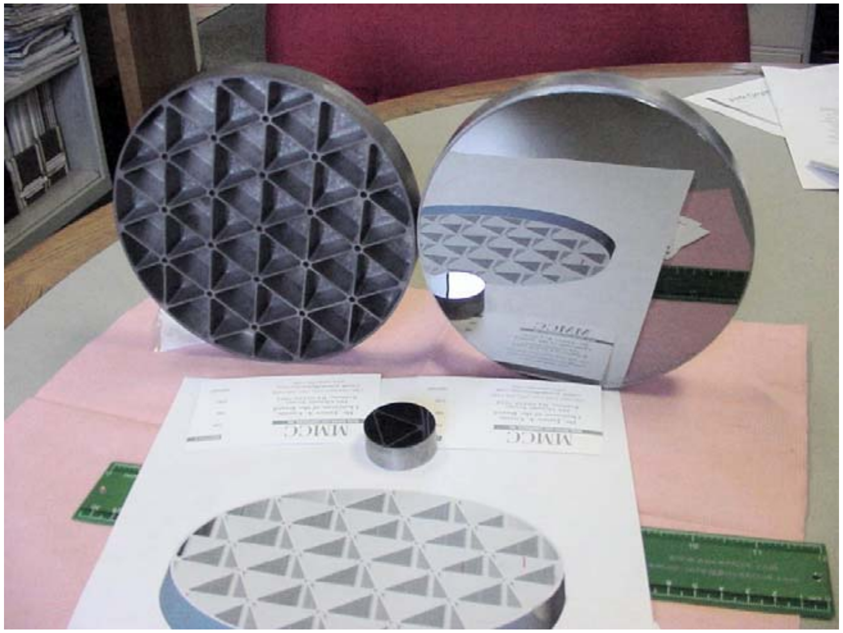
Plate 1, 310 mm dia. X 10 mm thick.

- **Total machining time=3 hr**
- **Face thickness = 2 mm, rib thickness + 2 mm**
- **Mass = 306 g**
- **Areal density = 5.04 kg/m^2**

Plate 2: 152 mm dia x 20 mm thick.

- **Total machining time = 1 hr.**
- **Face thickness =1 mm, Total thickness = 20 mm, Outer rim =2 mm, Inner ribs = 1.0 mm,.**
- **Mg/Gr = 211 g, Areal density in Mg/Gr = 11.56 kg/m^2**
- **Areal density with 0.5 mm SiC attached = 13.29.**
- **Further lightweighting (thinner outer rim, machined nodes, 0.5 mm face would reduce Areal Density to ~10 kg/m^2**

Attachment of Si and SiC Membranes to Lightweighted MetGraf Mg Substrates with Pre and Post Polishing Options



Pre-polished Si membrane bonded to lightweighted substrate. Areal density = 9.7 kg/m^2

SiC membrane bonded to Mg/Gr lightweighted substrate. Part to be Si coated and polished

Summary

1. Attachment of Si or SiC membranes to MetGraf Mg substrate is a viable approach
2. Low temperature Si deposition of MetGraf Mg substrate is also an acceptable approach
3. Si membrane hybrids have resulted in less than 10 kg/m^2 areal density
4. MetGraf Mg can be designed to CTE match a wide range of membrane surfaces
5. Thermal seasoning treatments can result in thermal stability over a wide range of operating temperatures