Fabrication of Functionally Graded Hybrid Composites

TEAM MEMBERS

Texas A&M University
- Ibrahim Karaman (Mechanical Engineering)
- Zoubeida Ounaies (Aerospace Engineering)
- Miladin Radovic (Mechanical Engineering)

University of Illinois – UC
- Scott White (Aerospace Engineering)

University of Dayton Research Institute
- Khalid Lafdi (Mechanical and Aerospace Engineering)

Virginia Tech
- Dan Inman (Mechanical Engineering)

Stanford University
- Fu Kuo Chang (Aeronautics and Astronautics)
Functionally Graded Hybrid Composites (FGHCs) – The concept

**Materials**
- Oxide ceramic
- Functionally graded ceramic/metal composite (GCMeC)
- Polymer matrix composite (PMC)

**Function**
- Thermal/Environmental Barrier Coating (Al$_2$O$_3$, ZrO$_2$, PS-ZrO$_2$)
- Self-healing of Protective Coating
- Gradual Change in Thermal Expansion
- Thermal Management
- Mechanical Damping
- Compressive Stress on Ceramic
- Load Bearing
- Host Sensors
- Damage Propagation Barrier
- Actively Cooled PMC with microvascular cooling functionality and/or High Temperature PMCs with polyimide matrices

**Self-healing**
- damaged protective oxide surface

15 µm thick protective Al$_2$O$_3$ surface layer formed after 10,000 heating cycles of Ti$_2$AlC

Ti$_2$AlC (light) + γTiAl (dark) as an example of MAX phase composite. (Produced by Spark Plasma Sintering)
Functionally Graded Hybrid Composites (FGHCs) – The team

Fabrication of Graded Ceramic Metal Composites (GCMeCs)
Radovic (TAMU – Ceramics and MAX phases)
Karaman (TAMU – Ti alloys and SMAs)

Fabrication of Polymer Matrix Composites (PMCs)
Actively Cooled High Temperature PMCs
White (UIUC), Ounaies (TAMU)

Joining of GCMeCs with PMCs
Ounaies, Radovic, Karaman (TAMU)
Lafdi (UDRI)

Embedding SHM modules and networks
Inman (VTU)  Chang (Stanford)
Fabrication of MAX Phases and GCMeCs

Materials: Ti$_2$AlC or Ti$_3$SiC$_2$ (MAX phases), Ti and SMAs (NiTi, NiTiPd, MnPd)

Forming MAX Phases

- **Reaction Sintering from Elemental Powders**
  - Hot Pressing (HP)
  - Hot Isostatic Pressing (HIP)
  - Spark Plasma Sintering (SPS)

- **Sintering of MAX Phase Powders (Ti$_3$SiC$_2$ and Ti$_2$AlC)**
  - HP, HIP,
  - Tape Casting
  - Slip Casting
  - Extrusion

- **Establish MAX phase porous preforms**
  - Infiltration of molten metal
    - Pressureless
    - Suction casting
    - Forced infiltration

- **A GCMeC layer**

- **Or co-sintering using SPS**
Fabrication of GCMeCs

TiAl/Ti$_2$AlC composites were produced by spark plasma sintering technology from mixed powders of Ti, Al and TiC.


Pressureless melt infiltration of Mg in Ti$_2$AlC porous perform.

Attributes of MAX Phases and GCMeCs

Very good damage tolerance
Large plastic deformation at high temps

Excellent machinability
High stiffness

Ultrasound attenuation is a function of the applied load – can be used for stress/health monitoring.

Ti based alloys or shape memory materials are expected to have excellent bonding with MAX phases, and provide high damping capacity and compressive stresses imposed at high temperatures due to shape memory effect.
Key Technical Challenges

- Control phase fractions and distribution including gradual change in phase distribution through the thickness;
- Control over phase distribution using different processing approaches:
  - Infiltration
  - Reactive sintering
  - Co-sintering
- Interfacial integrity between metal and ceramic particles and layers
  - Both candidate alloys and ceramics have Ti.
- Long term chemical compatibility between metal and ceramic phases, and between layers with different amount of phases;
- Full infiltration of molten metal into porous MAX phase preform.
PMC Layer
Actively-Cooled PMCs (AC-PMCs): Microvascular Composites

AC-PMC Concepts

- Short term: 2D planar array of embedded microchannels layered within a PMC
- Long term: 3D woven PMC architectures with integrated microvascular networks with sacrificial fibers co-mingled with reinforcement tows
2D Planar Arrays

- Leveraging of preliminary work accomplished under AFOSR MURI on *Microvascular Autonomic Composites* at UIUC

3 x 24 x 200 $\mu$m channel grid network
Preliminary Results

24 Parallel 200 μm Channels - 10 ml/min

Time (sec): 0

(2 °C between contour lines)
3D Woven PMC

- Microvascular networks embedded in 3D woven PMC that provide active cooling capability
- Sacrificial fibers integrated in z-tows (and/or x- and y-) that are removed during post-cure operation

Schematic of sacrificial fibers integrated with the 3D preform weave
Key Technical Challenges

• **Sacrificial fiber** development
  – Adequate hardness, extensibility, bend strength, etc.
  – Tailorable phase transition for post-cure removal
    • Thermal melt, thermal depolymerization and volatilization, solvent extraction

• **Optimization of vascular network** architectures
  – Easy post-cure removal + high thermal efficiency/low flow resistance

• **Weaving and co-mingling** of sacrificial and structural fibers
  – Collaboration: 3Tex, TEAM

• **Fabrication** of Composites
  – RTM/VARTM
  – Flow characterization and defect analysis (μ-CT, etc.)
PMC Layer
High-Temperature PMCs (HT-PMCs): Polyimide-Based Composites

Approach

- Several polyimide matrices with $T_g$ up to 400 °C including bismaleimide-based polyimides (Maverick Co. and AFRL)
- Available in powder or solution form

Processing

- Depending on viscosity:
  - Solution-cast, Thermal Cure then Autoclave
  - Solvent-assisted Resin Transfer Molding

Advantages

- Polyimides have good thermo-oxidative stability, resistance to moisture absorption, and relatively high moduli.
- Polyimides can withstand hot spikes up to two times their $T_g$. 
Key Technical Challenges

High-Temperature PMCs (HT-PMCs): Polyimide-Based Composites

- Viscosity of aromatic HT polyimides tends to be elevated which makes processing a challenge
  \[ \rightarrow \] Solvent-assisted processing of polymer to control viscosity.

- Composite processing by infusing fibers and fabric
  \[ \rightarrow \] RTM/VARTM or autoclave for composite processing.
  \[ \rightarrow \] Effect on $T_g$ and thermal/structural properties.

- Coupon fabrication using fuzzy glass or fuzzy SiC fibers for SHM
Joining GCMcC and PMC

- The GCMcC/PMC interface consists of bonding the pure metal to the polymer matrix.

- Three joining approaches are adopted:
  - bonding of metal to PMC using vertical nanocolumns followed by resin infusion,
  - bonding of metal to an intermediate fabric preform using vertical columns grown on both surfaces, with subsequent infusion of resin,
  - using Z-pinning technology
Joining GCMcE and PMC

Z-Pin Locking

- Metal infiltration in the porous ceramic using a hot press or SPS.
- Pressing die with small, high aspect ratio holes to create metallic micropillars as Z-pins.
- Alternately, micromachining to create Z-pins.

Mechanical locking as the polymer resin is flown on top of the metal layer then cured.
Joining GCMcC and PMC

Vertical Nanocolumns

Vertical nanocolumns are grown forest of carbon nanotubes using CVD.

1) Forest will be grown directly on metal layer
   • Polymer will be infused to fill voids between nanotubes
   • Pressing to the rest of composite preform then curing.

2) Forest will be grown on metal layer and fiber fabric
   • Polymer will be infused to fill voids between nanotubes
   • Pressing then curing.
SUMMARY
Collaboration is the key to success

Phase distribution, interface chemistry and properties, thermal and structural properties, etc.

- Initial material parameters
- Validation experiments

**Fabrication**

- 1000°C
- 300-400°C

**GCMeC**

**PMC**

**Multi-scale Characterization**

**Joining PMC w/ GCMeC, embedded SHM sensors**

**Structural Health Monitoring**

**Multiscale Structural Modelling**

Phase distribution and morphology, layer thickness, reinforcement and cooling network distribution, and desired functional grading for thermal management and structural properties