National Aeronautics and Space Administration

Fundamental Aeronautics Program

Supersonics Project

Lightweight Durable Engines – Overview

Dale Hopkins, Technical Lead
Glenn Research Center

2012 Technical Conference
March 13-15, 2012
Cleveland, Ohio

www.nasa.gov

Lightweight Durable Engines (LDE) "Big Picture"

What are we trying to do?

- Develop higher temperature capable, lightweight, and durable structural and functional materials with sound understanding of fundamental behavior; Seek opportunities for technology maturation and transition to use.
- Thoroughly test and characterize material and subelement behavior under relevant conditions; Seek opportunities for component concept development and technology validation/demonstration.
- Develop and validate physics-based, multi-scale behavior and life models; Incorporate models into computationally efficient "tool sets" that can "plug in" to CAE environments for higher-fidelity design.

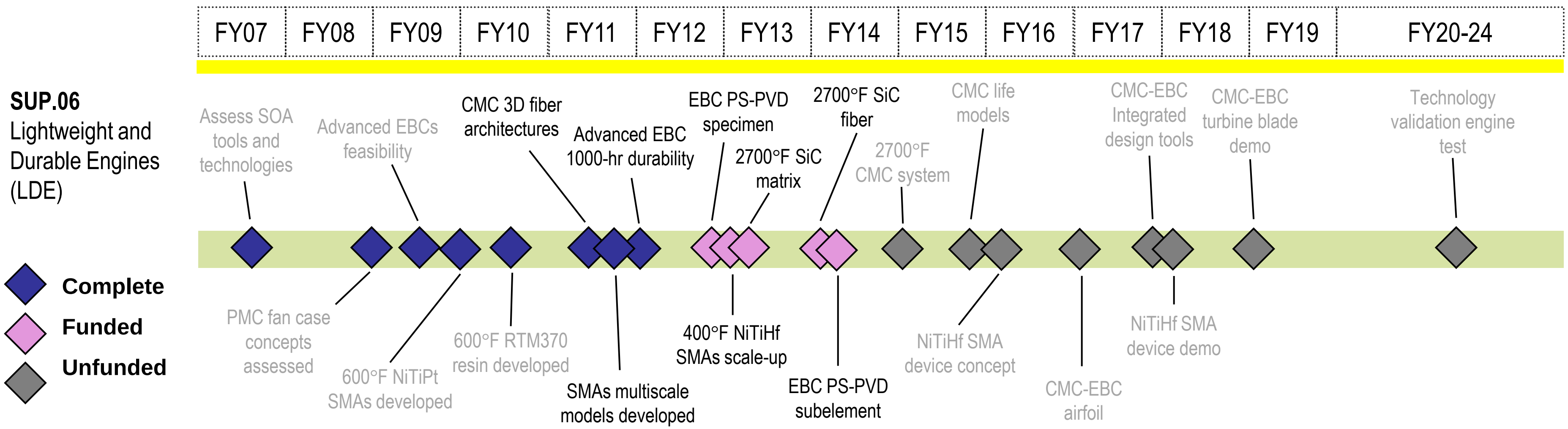
What is our approach?

- **Ceramic Systems for Turbine Blade/Vane Structures –** *3D* SiC/SiC Ceramic-Matrix Composites (CMCs) with *thin* integral Environmental Barrier Coatings (EBCs) for 2700-3000°F long-life operation, with lower or no cooling; Thin-film integrated sensors for temperature, heat flux, and strain measurements.
- **Functional Materials for Actuators/Adaptive Structures –** Higher temperature capable Shape Memory Alloys (HTSMAs) with high work output and high cycle stability for 200-600°F (350°C) operation; Higher temperature capable Piezoelectrics with high coercive field (induced strain) and stable electromechanical coupling for up to 750°F operation
- **Lightweight Composites for Case/Duct Structures –** Higher temperature capable, infusion process (RTM, RFI) friendly polyimide-class resins for PMC fan/inlet/bypass structures; Impact testing and modeling for engine containment structures.

What are the payoffs?

- Ceramic Systems and Lightweight Composites offer significant weight reduction and durability improvement for hot-section (e.g. turbine) and cool-/warm-section (e.g. inlet/fan/bypass) structures, respectively; Enables improvements in engine fuel efficiency and vehicle operating efficiency.
- Functional materials offer new opportunities for efficient implementation of variable-cycle/variable-geometry engine concepts, i.e. solid-state actuators and adaptive components for flowpath configuration/manipulation; Enables improvements in engine/vehicle system-level performance, efficiency, and environmental goals.

Lightweight Durable Engines (LDE) "Roadmap"



Recent Progress Supporting the Technical Challenge

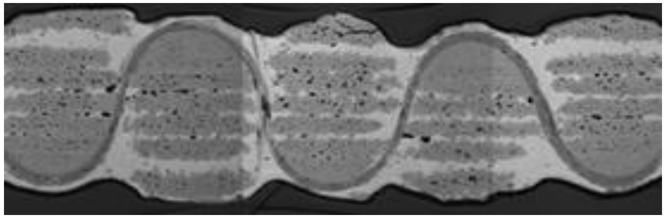
- Candidate 3D fiber architectures defined for SiC/SiC CMC specimen panels and airfoil subelements; manufacturing underway
- Advanced oxide-silicate EBC concept 1000-hr durability demonstrated
- Multiscale models developed to accurately predict SMAs transformation behavior
- Processing scale-up underway for NiTiHf SMAs
- PS-PVD processing trials underway for advanced EBCs
- SiC matrix development and SiC fiber treatment underway for 2700°F CMC

What are the intermediate and final exams to check for success?

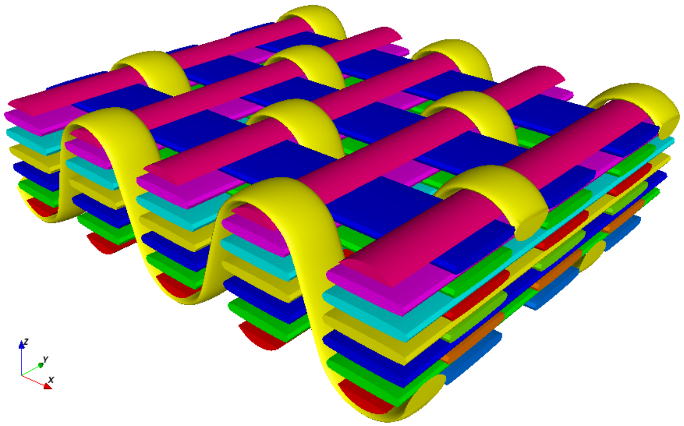
- Specimen and subelement lab-scale tests under relevant environments and loading conditions to assess property improvements, characterize behavior, and indentify critical failure mechanisms
- New behavior and life prediction models and design tools validated to test results.
- Prototype components manufactured, analyzed, and tested in collaboration with key stakeholders to assess technology benefits.

Key Milestone Completed:
3D Fiber Architecture Candidates for 2700°F HPT Vane Application

Design-Tools Developed for Visualizing 3D Fiber Architectures and Predicting Their Key Properties in SiC/SiC CMC Panels



3D-orthogonal architectures offer improved thru-thickness properties



	Repeating Unit Volume Dimensions, mm			Total Fiber Volume, %		
	H	W	L	Warp Stuffer	Fill Stuffer	Warp Weaver
Predicted	1.9	3.0	1.4	14.3	17.4	3.3
Measured	2.0	3.0	1.4	15.2	17.4	3.2

	Warp Weaver			Largest Perpendicular Tow Height, mm			AE Thru-Thickness Cracking Strength, MPa		
	R min, mm	Center Θ	Eff. Vol. % at Θ	X	Y	Z	X*	Y*	Z
Predicted	0.6	77°	3.0	0.12	0.17	1.4	119	122	26
Measured	0.5	75°	---	0.12	0.17	1.4	126	119	---

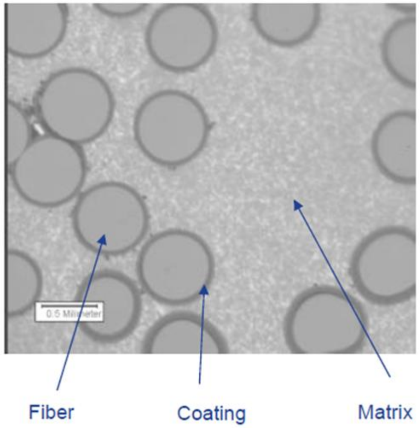
*** Assumed matrix residual stress = 20 MPa**

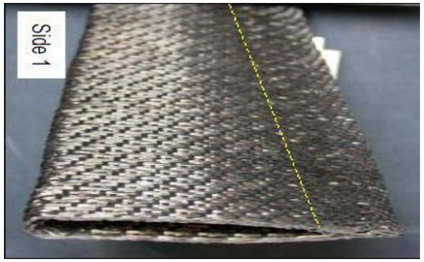
Key Milestone Status:
CMC SiC Matrix Material/Process with 2700°F Temperature Capability

Objective:

Optimize hybrid (CVI + PIP) SiC matrix to enable fabrication of CMCs with high strength, thermal conductivity and creep resistance at 2700°F, well beyond current state-of-the-art. Coordinate GRC research approach with complimentary AFRL CMC development program.

Activities Required for Milestone Completion	Due Date	Exit Criteria/Comments
Fabricate fiber preforms at TEAM vendor	04/30/12	Deliver flat panel (two 6x9 inch panels for each of six candidate 3D architectures) and airfoil-shaped preforms fabricated with current state-of-the-art silicon carbide fiber.
Infiltrate fiber preforms at Hyper-Therm vendor	06/30/12	Deliver airfoil preforms after melt infiltration. Deliver flat panel preforms after chemical vapor infiltration (CVI) coating of boron nitride and silicon carbide.
Infiltrate fiber preforms at EEMS vendor	08/30/12	Complete polymer impregnation and pyrolysis (PIP) infiltration of CVI-coated flat panel preforms and deliver hybrid matrix (CVI + PIP) composites for testing.
CMC matrix with 2700°F temperature capability developed	09/30/12	Hybrid-matrix thermal stability and improved matrix cracking stress level demonstrated at 2700°F.





HPT vane fiber preform

Status:

- Downselected six candidate 3-D fiber architectures for evaluation
- Shipped Sylramic fibers to vendor for weaving 3-D fiber preforms
- Reviewed CMC fabrication requirements with interface coating and PIP vendors

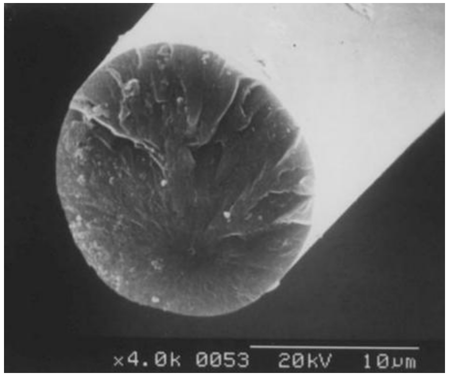
POC:
Ram Bhatt
3-5513

Key Milestone Status:
Advanced SiC Fibers with 2700-3000°F Temperature Capability

Objective:

Conduct theoretical and experimental studies to establish fabrication processes for a 2700°F SiC fiber and to ultimately develop a 3000°F Ultra High Temp SiC fiber. Assure that high-quality precursor fibers are available through collaboration with industry and Air Force Research Labs.

	Milestone	Due Date	Exit Criteria/Comments
SEED	Process facilities operational for UHT fiber	03/12	Initial runs performed through all UHT process facilities
SUP	GRC processes for 2700F Super Sylramic-iBN fiber re-established	03/12	2700F fiber properties at low and high temperatures validated
SUP	Design and demo Super-iBN fiber preforms for 2700F airfoil	04/12	Designs successfully fabricated at commercial weaver
SEED	UHT fiber and tow fabricated	06/12	UHT fiber properties at low and high temperatures measured
SUP	2700F fiber process transferred to industry	08/12	Industrial 2700F fiber properties validated
SUP	High-quality Sylramic precursor for 2700F fiber available commercially	09/12	COI Ceramics providing high quality Sylramic fibers



UHT Fiber Sintering Furnace

Status:

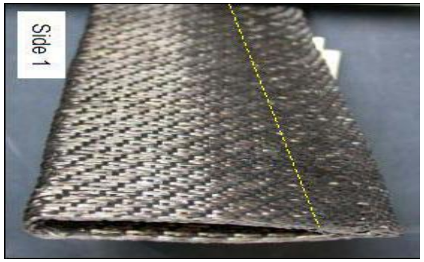
- Optimal sintering process for UHT fiber established
- In-house and vendor efforts underway for sintering 2700°F fiber precursor
- Completed chemical characterization of Lox M precursor fiber to determine oxygen, titanium and iron content prior to testing
- Conducted initial AES surface analysis of baseline fiber

POC: James DiCarlo, 3-5514

Key Milestone Status:
Advanced SiC Fibers with 2700-3000°F Capability

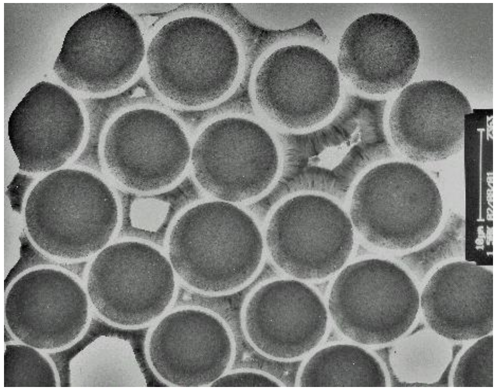
Fabrication Process for 2700°F "Super Sylramic-iBN" Fiber

Boron-Sintered SiC Fiber Preform **(formed from commercial "Sylramic" Fiber)** → **Preform Treatment in High-Pressure N_2** **(Boron removal for SOA creep-rupture resistance** → **Super Sylramic-iBN Preform** **(in-situ grown BN surface layer on each fiber for environmental protection)**



LPT Blade Preform

Preform Treatment Furnace

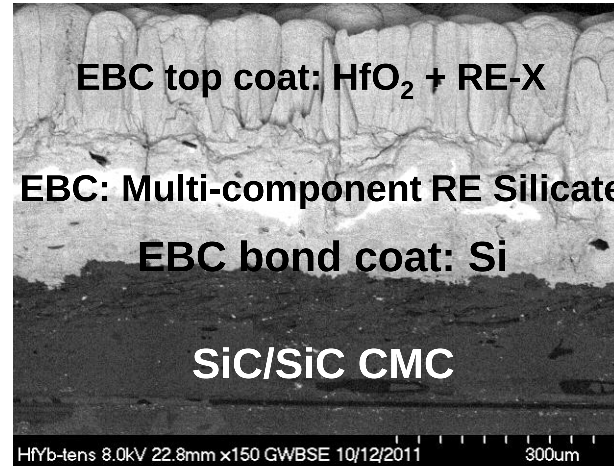


iBN coating between every fiber

2009 US Patent 7687016

Key Milestone Completed:
Advanced EBC Long-term Durability Demonstrated

Exit Criteria: EBC-CMC system survives 1000 hours (creep rupture) testing with EBC surface at 2700 F (1482 C).



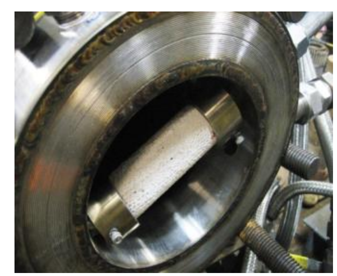
Approach:

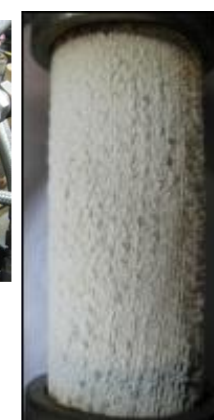
- **Coating Development:**
  - Advanced HfO_2-Si bond coat (vapor processed)
  - Advanced HfO_2-rare earth-silicate based EBCs (vapor and APS processed versions)
- **1000 hr durability (specimens)** of EBC-coated CMCs high heat-flux/tensile creep rupture tests
- **Coated CMC subelements demonstrated** (short duration feasibility tests)

EBC-coated CMC vane in laser rig testing

Accomplishments:

- Advanced EBC-coated CMC specimens survived 1000hr creep-rupture/laser high heat flux tests without failure.
  - Two key data sets: 2700 F/15 ksi test, 2750 F/20 ksi test
- Advanced EBCs (~10 mil thickness) processed via full-vapor deposition onto advanced 2.5D CMC airfoil subelements:
  - Survived 50hr exposure to laser high-heat-flux testing
  - Survived 50 hr exposure in high pressure burner rig testing with no measurable mass loss



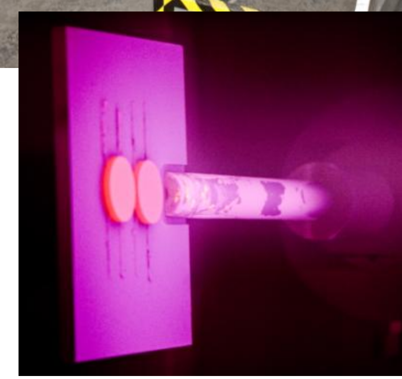


EBC-coated 2.5D CMC Sub-element in high pressure burner rig

➢ **Showed feasibility of durable EBCs for advanced CMC airfoil components.**

Key Milestone Status:
PS-PVD Processing Capability for Thin EBC on CMC Specimen

- "Standard" SOA for EBC Processing:
  - Bond coat: air plasma spray (APS)
  - EBC: electron-beam physical vapor deposition (EB-PVD)
- Benefits of PS-PVD:
  - Can apply plasma "splat" coatings AND vapor deposited coatings in **one system**
  - **Individual layer thicknesses < 10 μm:** for graded and multi-component coatings at much lower total thickness than SOA
  - Non line-of-sight deposition for **complex shapes**
- Unique PS-PVD system custom-built at NASA GRC for turbine engine coatings; operational as of FY10



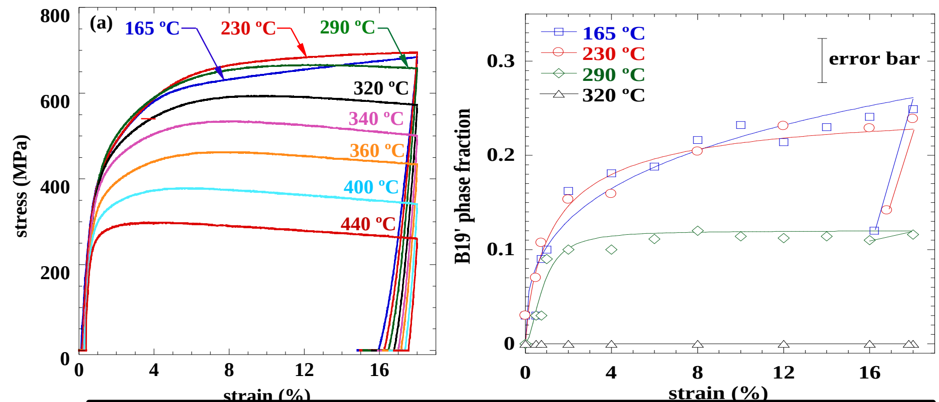
PS-PVD Deposition

- **FY12 (Key) Milestone: Plasma Spray-Physical Vapor Deposition (PS-PVD) EBC on a CMC specimen demonstrated**

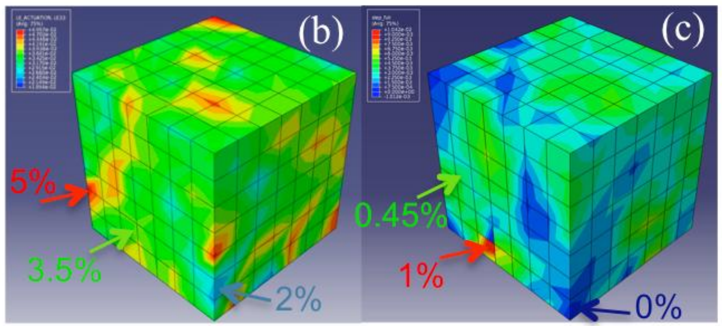
Key Milestone Completed:
Multiscale Computational Modeling Tools for Next Generation SMAs

Tool: In conjunction with The Ohio State University, a microstructure based finite element model (FEM) was developed and calibrated (mechanically and through *in situ* neutron diffraction techniques) for simulating combined phase transformation and plasticity in shape memory alloys

- The current approach offers a number of advantages over existing methods, the most critical being the ability to include crystal plasticity in austenite, as a competing inelastic mechanism to the phase transformation
- The model accurately predicts the simultaneous nucleation of martensite and plasticity during isothermal deformation of $Ni_{49.9}Ti_{50.1}$ (later demonstrated in detailed *in-situ* neutron diffraction studies), providing an explanation for residual strain during isobaric thermal cycling
- Model Details published: Manchiraju et al., *Acta Materialia,* **59** (2011) 5238
- Characterization details to be published: Benafan et al., *Acta Materialia,* (2012)



Experimental tensile data for $Ni_{49.9}Ti_{50.1}$ as a function of increasing temperature (left). Stress-induced martensite phase fractions determined by *in situ* neutron diffraction during loading and unloading (right) of select curves from the left.

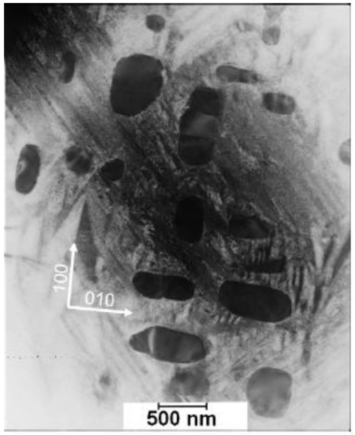


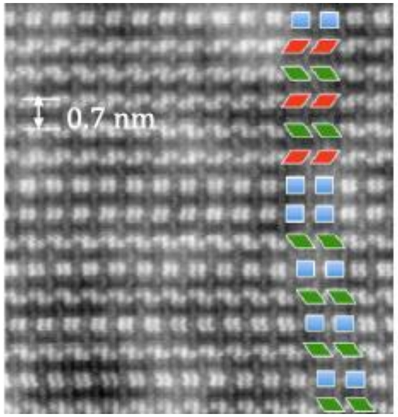
Simulations for a polycrystalline binary $Ni_{49.9}Ti_{50.1}$ SMA showing (b) actuation strain and (c) incremental effective plastic strain during a thermal cycle.

Key Milestone Completed:
Multiscale Computational Modeling Tools for Next Generation SMAs

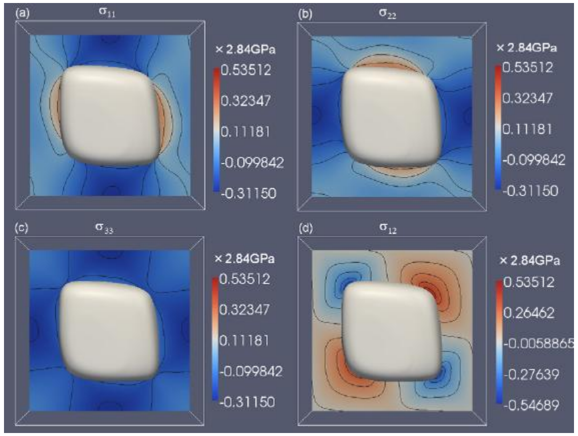
Tool: Next generation HTSMAs will rely on nano-size precipitates for strengthening and stability. A phase field model was developed for P-phase precipitation in a NiTiPt HTSMA, capable of simulating the shape and spatial distribution of the precipitate phase, along with compositional and stress fields surrounding them.

- In addition to accurately predicting the shape and distribution of second phase particles (as confirmed by electron microscopy observations), the model determined that both chemical and mechanical effects lead to an increase in transformation temperatures, with stress effects dominating at small precipitate sizes.
- NiTiPt microstructural details published: Kovarik et al. *Acta Materialia,* **58** (2010) 4660.
- Model Details published: Gao et al., *Acta Materialia,* **60** (2012) 1514.





Bright-field TEM image (right) and high angle annular dark field STEM image (left) of the P-phase (monoclinic) precipitate in a NiTiPt HTSMA along the [112] zone axis (bright regions are columns of Pt atoms).



Stress fields around a P-phase particle in a NiTiPt HTSMA: a) σ_{11} , b) σ_{22} , c) σ_{33} , and d) σ_{12}

Key Milestone Status:
Demonstrate Ability to Scale-up Processing of NiTi-20Hf HTSMA

Progress To Date:

- GRC has previously demonstrated the benefits and properties of a NiTi-20Hf alloy (Bigelow et al., Scripta Mater. 64 (2011) 725)
- Key to excellent properties identified as dispersion of nanometer size precipitates
- Master heat of material processed under direction of GRC and paid for by Boeing
- Initial 50 lb. heat of NiTi-20Hf successfully cast by Flowserve and successfully extruded into rod

Progress/Events Last month:

- Cast NiTi-20Hf ingots extruded in batch process into rod
- Extrusion rod has been submitted for machining into tensile samples for thermomechanical characterization
- Neutron diffraction used to determine the transformation/deformation mechanisms of NiTiHf – Manuscript submitted to *Metall. Maters. Trans.* describing initial results
- Characterization of in-house processed NiTiHf (& NiTiPd) HTSMAs continues

Approach – 1. Use NiTi-20Hf as HTSMA pathfinder (>100°C capability). 2. Determine whether melting process is scalable with same properties
3. Initiate durability testing and development of higher temperature alloys

Significant Findings Last Month:

- Composition of 50 lb.NiTi-20Hf heat confirmed – aim composition was achieved (e.g., 50.3Ni-29.7Ti-19.2Hf-0.93Zr (at.%))
- Interstitial content is orders of magnitude lower than GRC-processed material (107 ppm C, 32 ppm N, & 36 ppm O)
- Transformation temperatures highly dependent on prior thermal processing. Should only be "specified" in as-aged condition (M_s = 136 °C; M_f = 165 °C; A_s = 170 °C; A_f = 189 °C)

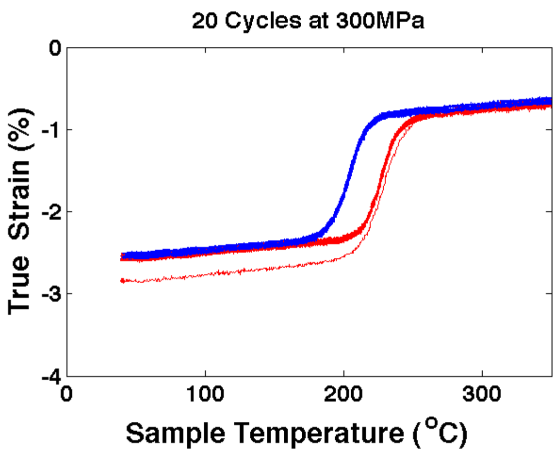
Issues:

1. Will need to spend significant effort/time to replan HTSMA work into new FAP Aeronautical Sciences project
2. Melting facilities down for multiple reasons
3. Machining delays accumulating
4. MTS rig due back from rehab vendor, substantial effort required to bring on line for durability testing

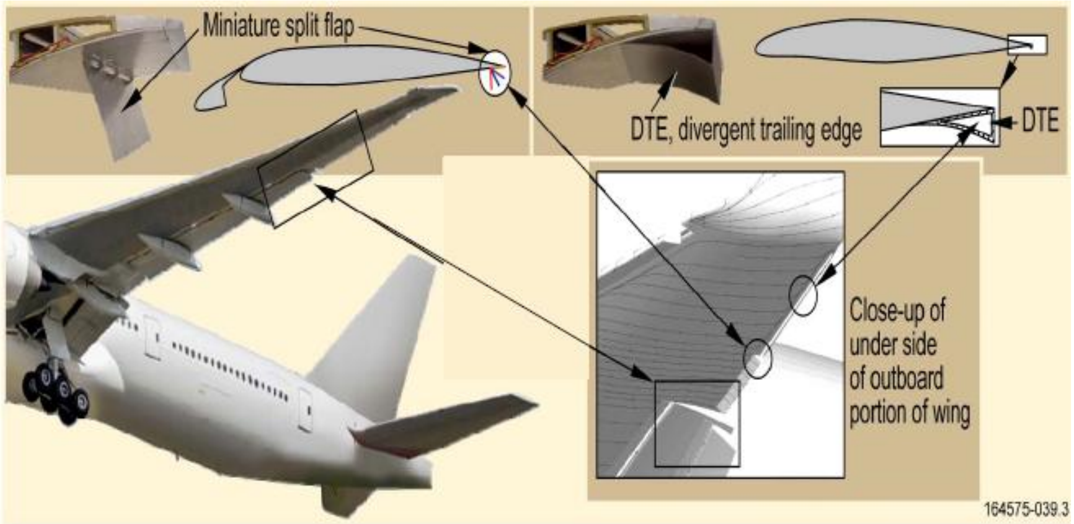
Key Milestone Status:
Accelerate Maturation of Next Generation NiTiHf HTSMA Technology

Tool Applications: Next generation HTSMAs, like the nano-precipitate reinforced NiTiHf alloys being developed at GRC, represent a breakthrough in shape memory alloy technology. The computational modeling tools previously developed will be used to accelerate the maturation of such systems.

- Future efforts will be focused on maturing HTSMA technology in collaboration with Boeing including: development of torque actuators, evaluation of the life and durability of such systems, scale-up of the processing of a >100 °C alloy for commercial aerospace applications, and development of a 200°C variant for supersonic (military) applications and nuclear safety switches
- The talk at the end of this session provides additional detail in the development of these novel, and highly engineered shape memory alloy systems



This NiTiHf HTSMA exhibits nearly perfect stability during cycling with no measurable unrecovered strain after 20 cycles at 300 MPa, ideal for solid state actuation applications.

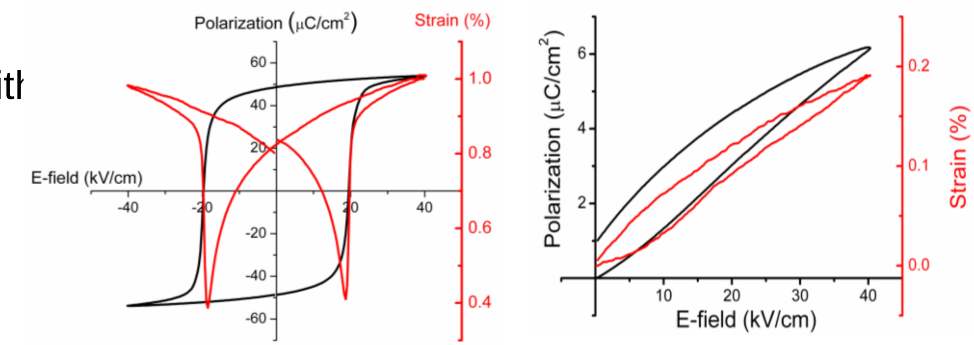


Boeing is interested in developing trailing edge flap systems based on SMA technology capable of tailoring wing performance to reduce noise and fuel burn at different flight regimes

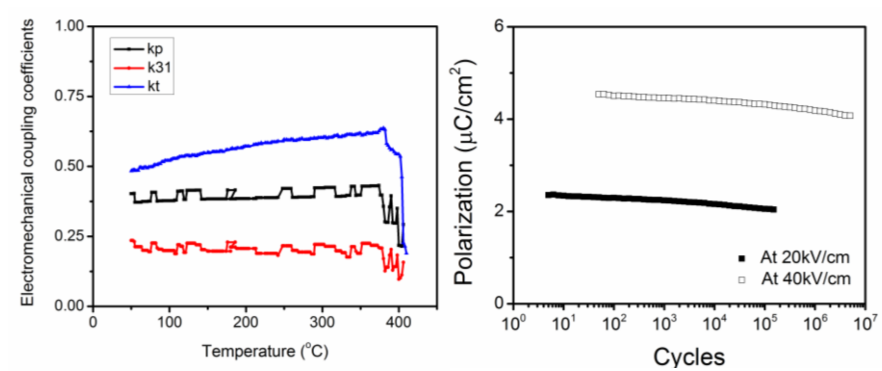
Key Milestone Status:

Develop New High Temperature Piezoelectric Materials for Actuators

- In conjunction with Case Western Reserve University, new high temperature compositions with state of the art properties have been developed. The composition is based on $BiScO_3$-$Bi(Zn_{1/2}Zr_{1/2})O_3$-$PbTiO_3$ system. The Curie Temperature is around 400°C.
- The material showed large field induced strain (nearly 0.2% at 40kV/cm). The piezoelectric coefficient is around 500 pm/V which is higher than other high temperature piezoelectrics with similar piezoelectric coefficients. The piezoelectric coefficient is close to that of soft PZTs but has much higher operating temperature (i.e. ~150°C for PZT)
- These new piezoelectrics do not depole up to their 400°C. The electromechanical properties are large in comparison to other piezoelectrics that have similar electrical hardness. The coercive field is around 20kV/cm at room temperature. The hysteresis loops are square and single crystal like indicating a high level of domain stability upon removal of electric field. The remnant polarization is near $50 mC/cm^2$, a value that is extremely high.
- *<u>A provisional patent application has been submitted</u>*



Field induced polarization and strain for composition in $BiScO_3$-$Bi(Zn_{1/2}Zr_{1/2})O_3$-$PbTiO_3$ system. Bipolar (left) behavior shows large remnant polarization and coercive field. Unipolar (right) behavior shows large high field piezoelectric coefficient.



Electromechanical coefficients (left) as a function of temperature show a depoling temperature of 400°C. Fatigue measurements at consecutive cycles under 20kV/cm and 40kV/cm (right) show the long term stability.

New NASA SBIR Awards Related to LDE

2011 SBIR Phase I Award – Direct Vapor Technologies International, Inc.

Innovative Processing Methods for the Affordable Manufacture of Multifunctional High Temperature Coatings

- Multi-layered T/EBC coating designs with multi-functional protection
- Novel processing using EB-PVD techniques enabling enhanced coating adhesion and advanced coating architectural, compositional, and microstructural control

2011 SBIR Phase I Award – Arcast, Inc.

Alloying and Casting Furnace for Shape Memory Alloys

- Melting, casting, and alloying furnace for processing Ti-based SMAs using cold crucible techniques for high purity without ceramic contamination
- Combination arc melting and induction processes enabling SMA material to be fully alloyed from elemental feed stock
- Complete melting, alloying, and casting processes within a single vacuum/atmospheric chamber reducing oxygen contamination

R&D Collaborations Complementary to LDE

Ceramic-Matrix Composites (CMCs);

- **Air Force/AFRL (SAA)** – collaboration on 2700 F CMC development
- **GE (SAA)** – testing, analysis, and modeling of CMC properties and failure modes
- **Rolls-Royce (SAA)** – characterization of CMC properties and durability
- **Pratt & Whitney (informal)** – collaboration on advanced SiC fiber and matrix development
- **T.E.A.M. Textile Engineering & Manufacturing (NASA NRA, follow-on contract)** – continue manufacturing process optimization for 3D SiC fiber preform architectures

Environmental Barrier Coatings (EBCs);

- **Department of Energy/NETL (SAA)** – Coating formulation support and testing of new TBCs for land-based power generation turbine advanced technology development
- **Rolls-Royce LibertyWorks (SAA)** – testing of EBCs for aircraft engine turbine advanced technology development
- **Siemens Energy (SAA)** – testing of TBCs for land-based power generation turbine technology development
- **Sulzer Metco (SAA)** – testing of low-thermal-conductivity TBCs (NASA patented) processed by Sulzer Metco under Air Force turbine engine technology enhancement
- **Penn State University (NASA GSRP)** – advanced TBCs development using PS-PVD processing
- **University of Akron (NASA GSRP)** – environmental durability of EBC coated CMCs with thermo-mechanical gradients

R&D Collaborations Complementary to LDE (cont'd)

High-Temperature Shape Memory Alloys (HTSMA);

- **Sandia National Laboratories (reimbursable SAA)** – develop HTSMA thermal safety switches for nuclear weapons.
- **University of Alabama (NASA EPSCOR)** – perform advanced characterization of precipitate reinforced HTSMA.
- **University of Kentucky (NASA EPSCOR)** – study ultra-high strength HTSMA single crystals and polycrystalline alloys.
- **Colorado School Mines (NASA GSRP)** – study basic microstructure-property relationships in NiTiPt alloys.
- **Ohio State University (NASA NRA, now informal w/ DOE, NSF support)** – continue basic characterization and application of microstructure/continuum behavior models to new NiTiHf alloys.
- **Texas A&M University (informal, CASMART consortium w/ Boeing et al.)** – basic characterization of HTSMA with new focus on precipitate reinforced NiTiHf alloys.
- **Boeing (informal, CASMART consortium w/ TAMU et al.)** – further develop NiTiHf alloys and mature technology for aviation applications.
- **University of Central Florida (NASA NRA, now informal w/ LANL support)** – basic *in situ* characterization of high-temperature binary NiTi alloys by neutron diffraction.
- **Northwestern University (NASA GSRP, now informal)** – basic characterization of high-temperature binary NiTi alloys and development of crystal/micromechanics models for deformation behaviors.

R&D Collaborations Complementary to LDE (cont'd)

High-temperature Infusion-processable Polyimide Resins and PMCs;

- **Clark Atlanta University** (informal) – RTM processing of polyimide PMCs.
- **Boeing** (cost-share contract) – RFI processing of polyimide PMCs.
- **Maverick Corp.** (SAA) – polyimide resin formulation and processing scale-up.

Impact Testing and Modeling for Engine Containment Materials/Structures;

- **FAA/William J. Hughes Technical Center** (SAA, now informal) – engine containment technology.
- **The Ohio State University** (NASA NRA, now informal) – high strain rate material characterization testing.
- **George Washington University** (informal) – impact modeling.
- **Livermore Software Technology Corp.** (informal) – LS-DYNA transient dynamics FEA code application to engine containment impact modeling; LS-DYNA Aerospace Working Group.

LDE Session Presentations

Wednesday

4:00 – 4:30 *“Recent Progress and Future Direction of CMCs Research and Development at NASA Glenn”*

Dr. Joseph Grady, NASA GRC

4:30 – 5:00 *“Progress in NASA’s Development of Advanced Environmental Barrier Coatings for CMC Turbine Components”*

Ms. Joyce Dever, NASA GRC

5:00 – 5:30 *“Pitfalls and Potential for Developing Stable High-Temperature Shape Memory Alloys Through Nano-Precipitate Strengthening”*

Dr. Ronald Noebe, NASA GRC

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