Naval Materials S&T

Comments to the University Materials Council

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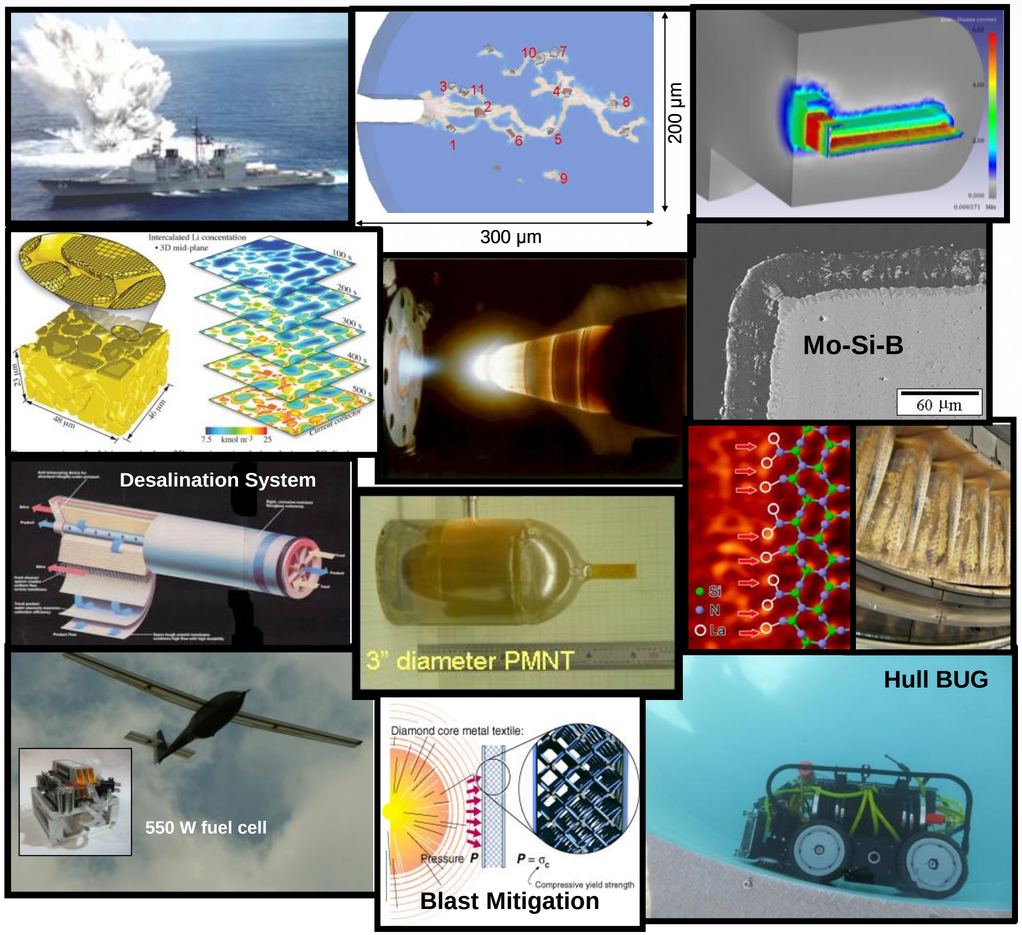
Director, Naval Materials Division
18 May 2017

Naval Materials S&T

Integrated theoretical, computational and experimental programs to understand and develop the physics, chemistry, materials and processing that confidently meet critical naval needs



High Performance Functional Materials

- Power Generation & Energy Storage Materials
  - Electrochemical Materials
  - Polymeric and Organic Materials
- Piezoelectric Materials

High Performance Structural Materials

- Structural Metallic, Structural Cellular and Composite Materials
- High Temperature Turbine and Ultra-high Temperature Materials
- Welding and Joining
- Optical Ceramics

Environmental Quality

- Anti-fouling Release Coatings
- Solid and Liquid Waste Treatment

Optimization from Design thru System Life

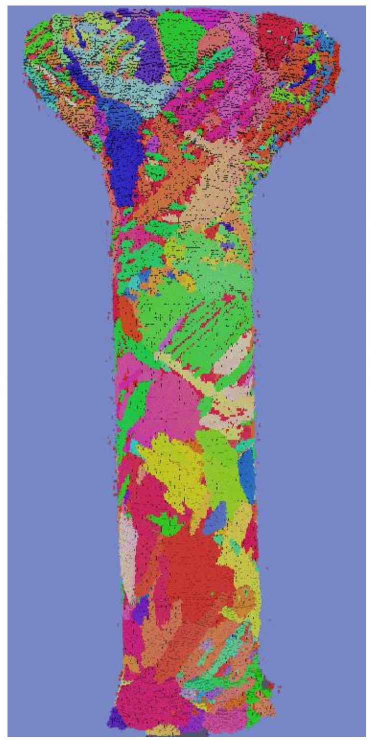
- Computer Aided Materials Design
- Scarce Element Mitigation Strategies
- Solid Mechanics and Fatigue
- Non-Destructive Evaluation and Prognostics
- Additive Manufacturing
- Integrated Computational Materials Engineering

Mechanical Properties, e.g.

Common Engineering Concepts?

Reality?

EBSD image



MIL-HBK-5H

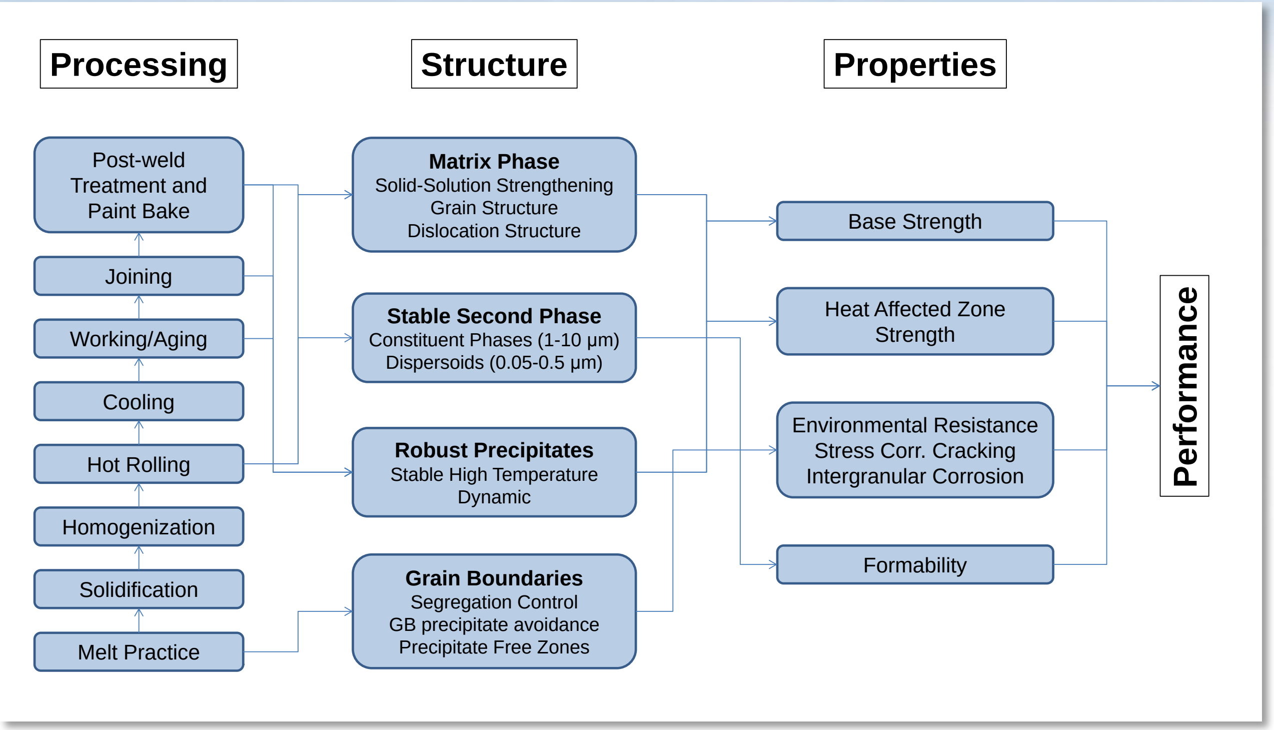
Table 5.4.1.0(b). Design Mechanical and Physical Properties of Ti-6Al-4V Sheet, Strip, and Plate

Specification	AMS 4911 and MIL-T-9046, Comp. AB-1					MIL-T-9046, Comp. AB-1			
Form	Sheet		Plate			Sheet, strip, and plate			
Condition	Annealed					Solution treated and aged			
Thickness, in.	≤ 0.1875		0.1875-2.000		2.001-4.000	≤ 0.1875	0.1875-0.750	0.751-1.000	1.001-2.000
Basis	A	B	A	B	S	S	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	134	139	130[a]	135	130	160	160	150	145
LT	134	139	130[a]	138	130	160	160	150	145
F_{ty}, ksi:									
L	126	131	120	125	120	145	145	140	135
LT	126	131	120[a]	131	120	145	145	140	135
F_{cy}, ksi:									
L	133	138	124	129	124	154	150	145	...
LT	135	141	130	142	130	162	...	...	...
F_{su}, ksi	87	90	79	84	79	100	93	87	...
F_{bru}, ksi:									
(e/D = 1.5)	213[b]	221[b]	206[b]	214[b]	206[b]	236	248	233	...
(e/D = 2.0)	272[b]	283[b]	260[b]	276[b]	260[b]	286	308	289	...
F_{bry}, ksi:									
(e/D = 1.5)	171[b]	178[b]	164[b]	179[b]	164[b]	210	210	203	...
(e/D = 2.0)	208[b]	217[b]	194[b]	212[b]	194[b]	232	243	235	...
e, percent (S-basis):									
L	8[c]	...	10	...	10	5[d]	8	6	6
LT	8[c]	...	10	...	10	5[d]	8	6	6
E, 10^3 ksi	16.0								
E_c, 10^3 ksi	16.4								
G, 10^3 ksi	6.2								
μ	0.31								
Physical Properties:									
ω, lb/in.^{3}	0.160								
C, K, and α	See Figure 4.5.1.0								

a The rounded T_{99} values are higher than specification values as follows: F_{tu}(L) = 131 ksi, F_{tu}(LT) = 132 ksi, and F_{ty}(LT) = 123 ksi.
b Bearing values are "dry pin" values per Section 1.4.7.1.
c 8%—0.025 to 0.062 in. and 10%—0.063 in. and above.
d 5%—0.050 in. and above; 4%—0.033 to 0.049 in. and 3%—0.032 in. and below.

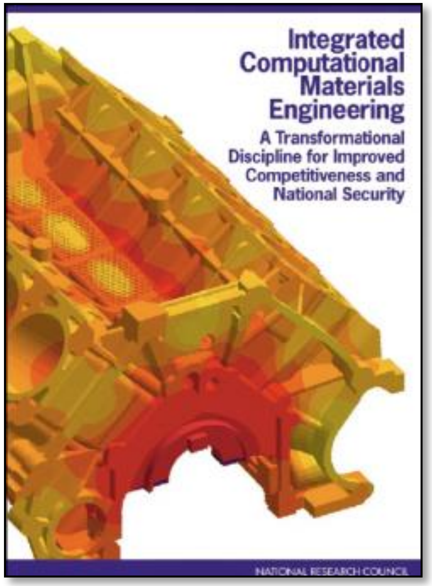
Adapted from D. Furrer, April 2013

Integrated Computational Materials Engineering (ICME)



Integrated Computational Materials Engineering provides the framework for understanding and communicating

- evolution of microstructure,
- material properties and behavior,
- material design capability,
- component performance, and
- component degradation.

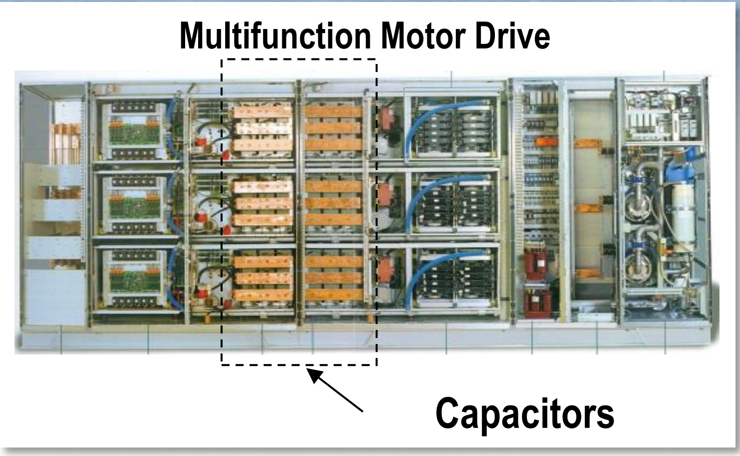


NRC Report on ICME (2008)

Dielectric Materials for Capacitive Energy Storage

Focus on improving energy storage density through improved dielectric materials for cost effective, large scale systems.

- Multi-scale computation and computer aided discovery based on permittivity and breakdown characteristic optimization
- Theory guided synthesis, characterization and feedback to theory
- Understanding thermal stability
- Minimizing loss



Capacitors can make up 50% of the volume of power storage and conditioning systems.

Major Participants

Penn State

CWRU and NRL

General Atomics, PolyK Technologies, Polymer Plus

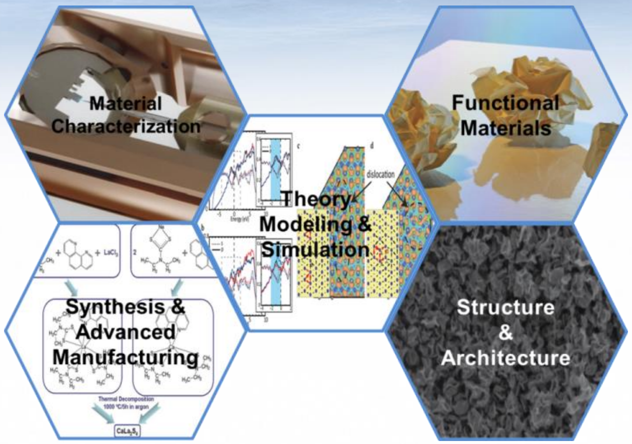
Progress

- Discovered and developing dielectric films based on terpolymer fluoropolymers, multilayer extrusion, aromatic thioureas and related systems and group IV metal containing dielectrics (Si, Sn, Ge).
- Maturing multilayer extruded films and higher temperature fluoropolymer blend systems for optimized manufacturing
- Nanocomposite approach to reduce leakage current at high temperatures

Nanomaterials

Focus on understanding and optimizing the mesoscale and bulk properties of materials with internal structures at the nanoscale.

- Both structural and multifunctional nanomaterials, metals and ceramics
- Multi-scale computation guiding and describing processing and stability of structures at mesoscale and beyond
- Advanced characterization techniques
- New synthesis and assembly routes
- Novel assembly and manufacturing, including repair tools



Inherently multidisciplinary, integrating experimental and computational approaches

Major Participants

Rutgers U
U Colorado
Johns Hopkins U
UC Berkeley
Integran Technologies
Purdue U
MIT
NRL
NAVSEA

Progress

- Formulated a Frenkel pair model to explain anomalous lattice expansion observed during electric-field-assisted sintering of oxide ceramics.
- Maturing Electroplasticity as a metal forming technique.
- Exploring shipboard *in situ* repair of Cu-Ni piping in heat exchangers, fire suppression mains, etc

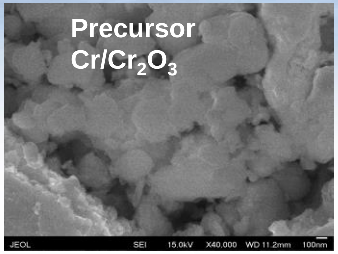
AM of Structural Non-oxide Ceramics by Photothermochemically-assisted Reaction Bonding

Objective

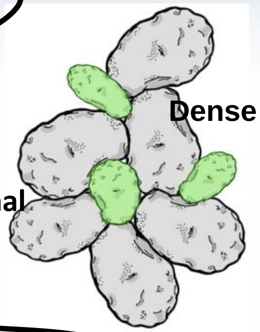
- Develop photothermo-chemically-assisted reaction bonding techniques for additive manufacturing (AM) of non-oxide ceramics.

Approach

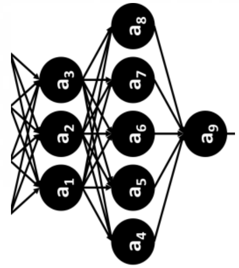
- A binder-free, dense ceramic formed from precursor materials.
- Binary phases will be converted to the same non-oxide ceramic.
- Process optimization will be accomplished using neural networks.



Reactive Precursor Systems

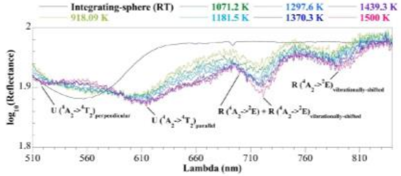


Reaction Pathways and Thermal Conversion

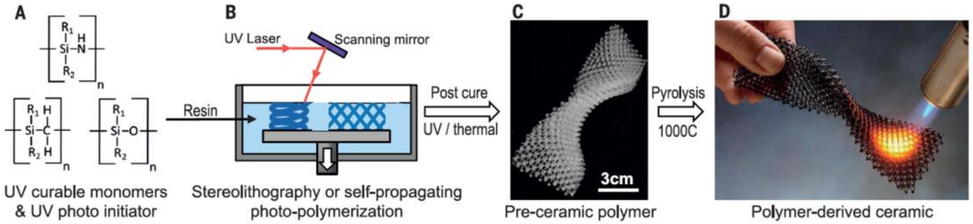


Machine Learning for Process Optimization

Laser Processing Studies for AM Compatibility



State of the art:



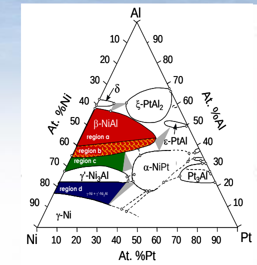
(Z. C. Eckel et al., *Science* 2016)

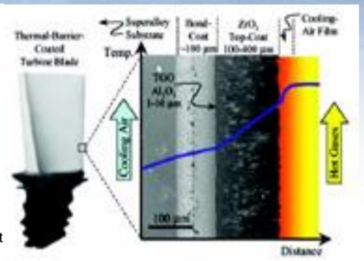
(Spicer Group)

Distribution Statement A: Approved for public release (DCN 43-2780-17)

Propulsion Materials

Focus on understanding and obviating the damage mechanisms active in the severe temperature and chemical environment in which Naval turbine engines operate to optimize performance (thrust:weight ratio) and confidently minimizing maintenance requirements.





Inherently multidisciplinary, multi-component for confident turbine efficiency in a hostile environment.

- Create and develop materials for ship and aero turbine engine operating temperatures up 1500oC.
- Characterizing the thermodynamics and kinetics of materials interactions affected by temperature, environment, materials chemistry, and stress
- Integrated theoretical and experimental approach to computational models for design of materials, materials processing, and life prediction
- Establish tools to understand and quantify highly coupled degradation mechanisms as a function of numerous variables (e.g. temperature, temperature gradients, stress, contaminants, interdiffusion, interfacial mobility, thermal stability, oxide growth rates, corrosivity)

Progress

- Characterization and understanding of coating strength and grain structure influence on fatigue life under conditions where hold times are present
- Strong bond coats and interdiffusion zones increase life, particularly for thin sections
- Improved understanding of CMAS interactions with TBCs/EBCs leading to materials solutions for enhanced coating durability and improved life prediction models, discovery of CMAG in ship engines

Marine Gas Turbines Materials

Project TOTAL SAVINGS = $65M to $76M/year

Objective / Goal

Lower Total Ownership Costs (TOC) by developing advanced materials package capable of minimum 3X engine life over current gas turbine (GT) materials set

Technical Approach

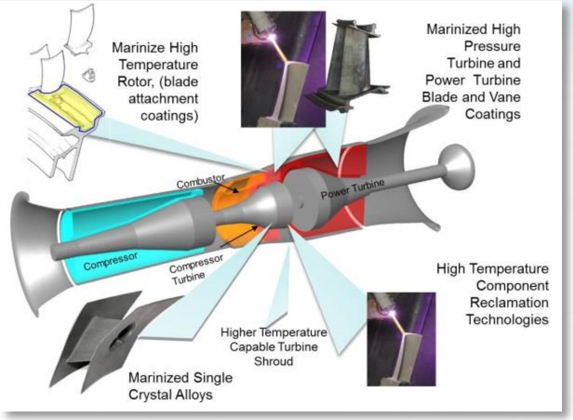
- Leverage ONR gas turbine materials development program
- Shipboard GT Marinization Package for Higher Temperature, Higher Pressure Operations
  - *Marinized High Temperature Rotor Alloys*
  - *Oxidation/Hot Corrosion Resistant Blade/Vane Coatings*
  - *Marinize Single Crystal Alloys*

Recent Accomplishments

- Universities beginning coating development, burner rigs at UVA and UC Irvine are running coating /alloy tests evaluating corrosion resistance in RR baseline and new advanced coating systems
- RR and GE evaluating disks, alloy and coating

~ 25,000 Hrs (Repairable)

4300 Hrs (Non-repairable)



Key Milestones / Projected Transition

- Integrated upgrade materials package (marinized rotor, marinized single crystal alloys, oxidation/hot corrosion-resistant coatings)
- NAVSEA specification to backfit upgrade package during depot MTBR and for future USN/USMC new construction engines

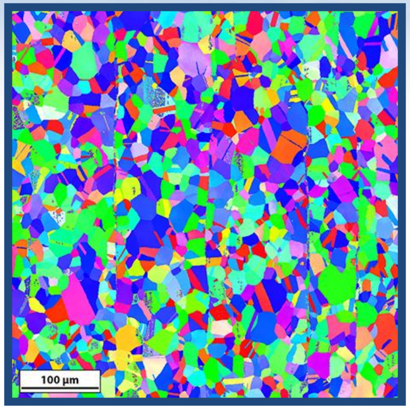
Additive Manufacturing Materials & Processes

Focus on establishing the scientific basis for processing confidence, enabling the rapid qualification and certification of AM components,and

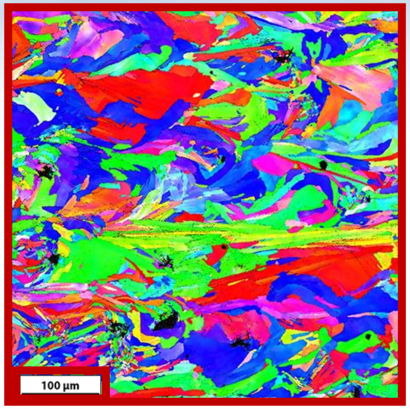
expanding the design space for AM fabrication including tailored geometries, microstructure and properties.

- Multi-scale predictive models for AM materials and processes, enabling engineering applications
- Materials optimized explicitly for AM for Naval applications
- Harnessing the highly coupled and complex design, structure, process, and performance relationships for AM fabricated parts through computational modeling and materials characterization
- Establish verification and validation for robust computational models to enable an accelerated qualification framework for AM parts

Microstructural Differences in AM



Wrought 316 Stainless Steel



Additive DMLS 316 Stainless Steel

Microstructural complexity must be understood and controlled.

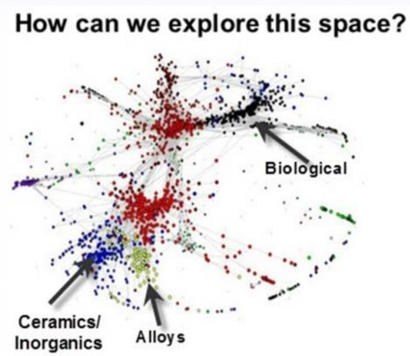
Progress

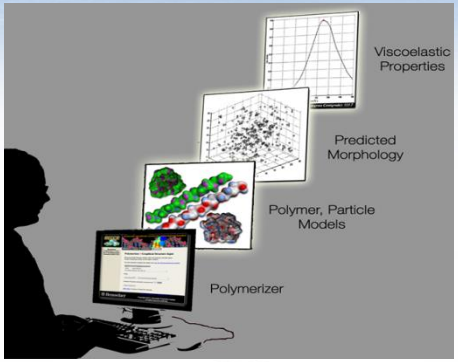
- Large scale AM for molds and tooling applications; including development of a full scale optionally manned technology demonstration
- Flight critical AM part demonstration
- Understanding impact of residual stress

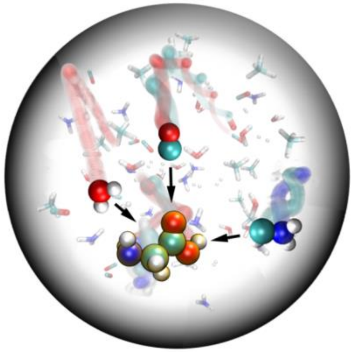
Computer-Aided Materials Design

*Focus on establishing the scientific basis for the d*iscovery of new materials, improving existing materials, and rapid insertion (ICME)

- High Throughput Screening
  - Automation & new algorithm
  - Off-lattice scaling
- Informatics
- Multiscale Simulation







Multi-Scale Models/Simulation

Progress

- Rensselaer Materials Informatics Tools now being used by Lockheed-Martin for discovery/design of polymer composites
- AFLOW Automated Flow for Materials Discovery
- RAPPID (phase diagrams): in progress; beta tests 2017
- “Automated Discovery and Refinement of Reactive Molecular Dynamics Pathways” published, 2016
- PROFESS 3.0 (Princeton Orbital-Free Electronic Structure Software) released, 2016

Major Participants

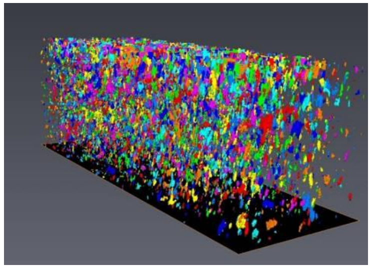
- Princeton, Stanford, Chicago, Brown, Duke, BYU, RPI, Maryland

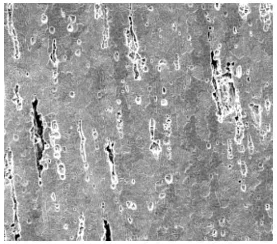
Structural Metals

Focus on developing and extending the knowledge base for the design of metal alloys, alloy processing and joining approaches for accelerated engineering application in high-performance, affordable systems.

- Structure↔processing ↔ properties ↔ performance relationships for materials
- Characterization and quantification of microstructure features and their statistical correlations
- Advanced tools for characterization, physical and computational
- Development of model-based design and optimization approaches for materials and systems
- Verification and validation of data and models to ensure robust design
- Uncertainty quantification

Creep Damage during simulated fire exposure in Al 5083: SEM and X-ray Tomography





Capturing the heterogeneity of alloys for improved component design and asset management.

Progress

- Advanced high-strength steel for CVN flight-deck applications
- Demonstration of Ti-alloy valve cores via advanced powder processing
- Shipyard demonstration of friction-stir joining of steel plate

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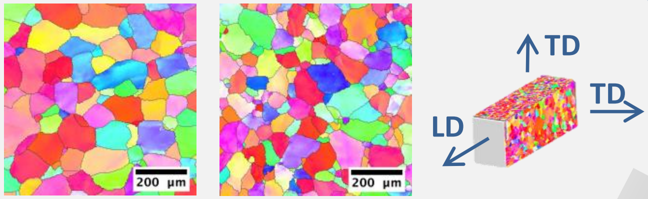
ICME for Design & Prediction

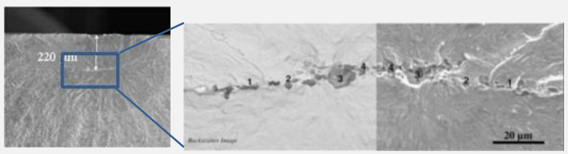
Alloy and Process Design Tool Feedback

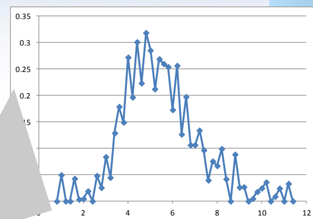
Manufacturing Optimization

Damage Models for Prognosis



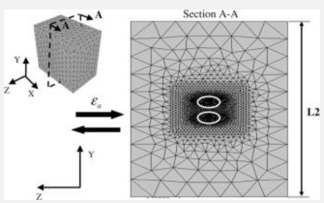
Ti 4 processing effects



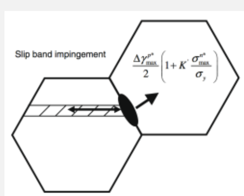


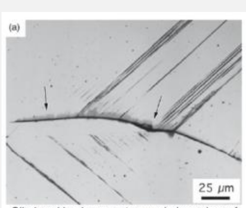
Salient Microstructural Feature Size & Distribution

Processing Models and Microstructure Evolution Models

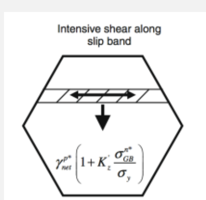


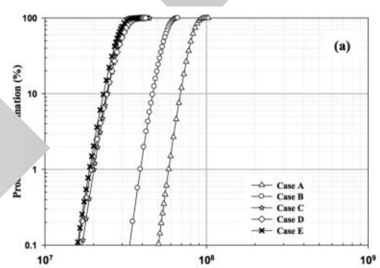
Physical Models for Damage Nucleation



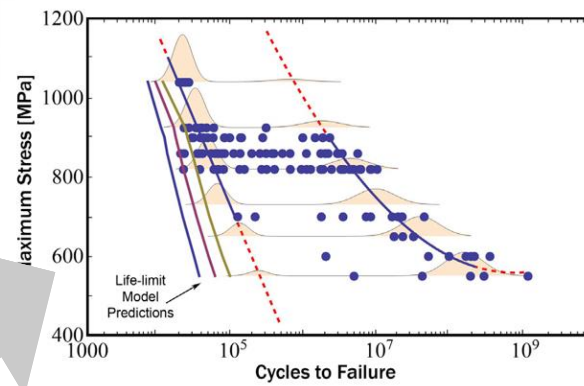


Slip band impingement on grain boundary of polycrystalline nickel [26].





Damage Initiation Probability

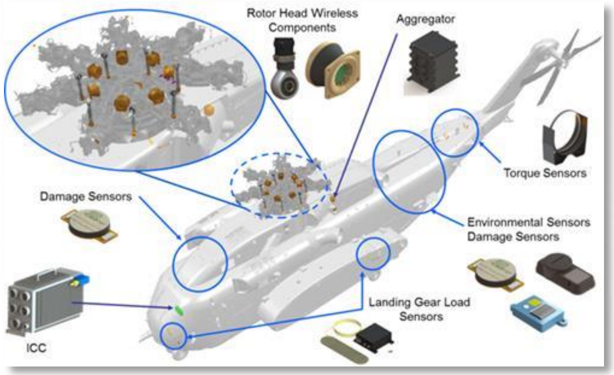


Multi-Mechanism Failure Prediction

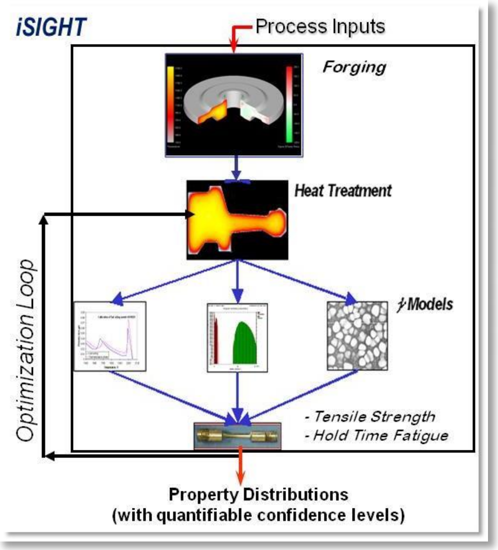
Asset Management in Digital Age

Cyber-Physical Environment will enable state-awareness for optimal design, manufacture, maintenance and capability assessment of materials, components, systems and platforms.

Platform State Awareness | Material State Awareness



Prognostics



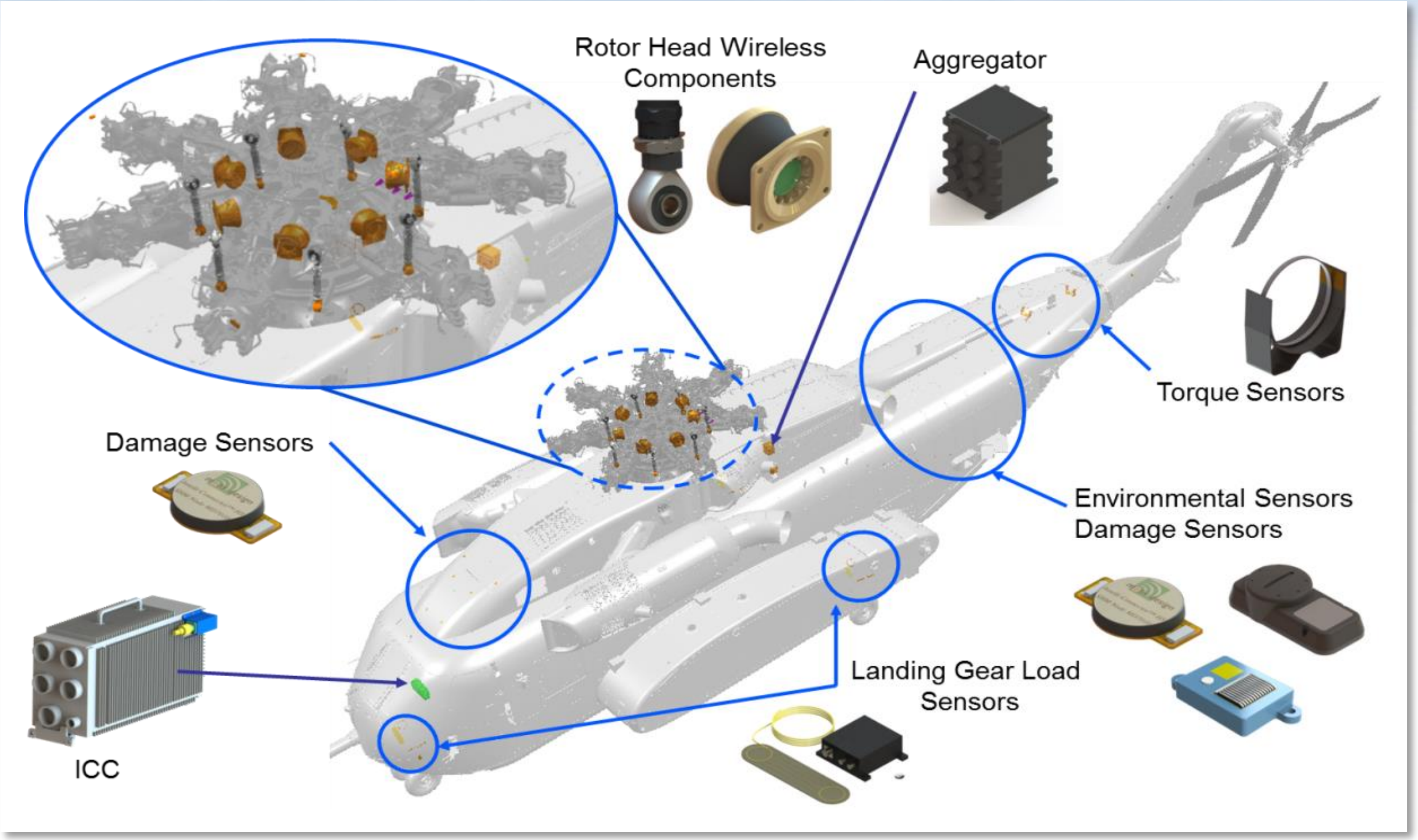
ICME

Approach:
Start with the 60% solution, aim high, and iterate frequently.

Prognostics: Integrated Hybrid Structural Management System (IHSMS)

Capabilities

- Gross Weight (GW) and Center of Gravity (CG) measurements
- Load/load-history tracking for dynamic components and airframe hot spots
- Damage detection and monitoring
- Damage growth and criticality prediction
- Micro-climate environmental monitoring
- Expanded fleet/asset management



Developed and demonstrated a single integrated structural health fleet management system for the CH-53K platform, combining sensors an algorithms to track and assess (cycle-by-cycle) loads, damage, environment, usage and health of the rotor and fuselage

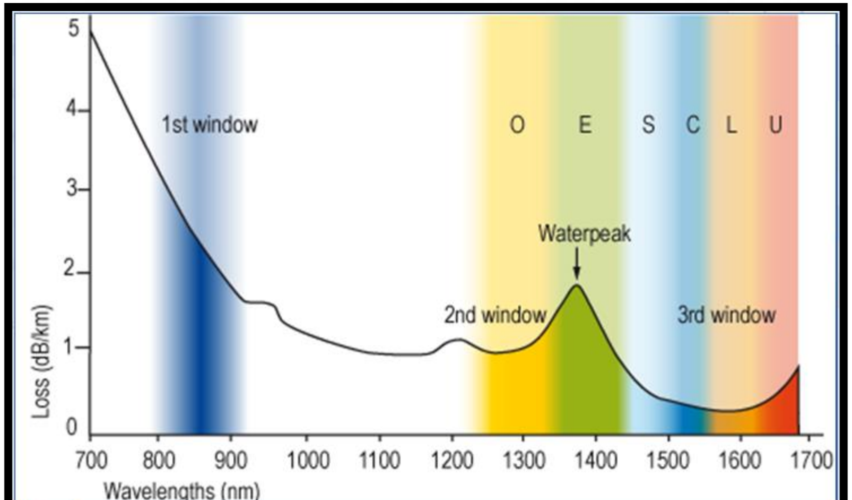
Fiber Optic Sensors

Enabling multiple simultaneous measurands (Temp, Strain, Vibration, Impacts, Acoustic Emissions)

Measurand	TOW	Temp	Flutter	Strain	Accel.	Vibrat.	Impact	AE
Frequency Range (Hz)	0.01 – 0.1	0.1 – 1	1- 10	10 - 100	100 – 1k	1k – 10k	10k - 100k	100k – 1M

FOBG Strain Sensors have cross sensitivity with Temperature

ε (micro-strain)	Δλ (nm)	ΔT (ºC)
1,000	1	100



	Optical band	Wavelengths
O	(Original)-Band	1260 nm – 1360 nm
E	(Extended)-Band	1360 nm – 1460 nm
S	(Short)-Band	1460 nm – 1530 nm
C	(Conventional)-Band	1530 nm – 1565 nm
L	(Long)-Band	1565 nm – 1625 nm
U	(Ultralong)-Band	1625 nm – 1675 nm

Multi-Performer Programs

MURIs:

- *Materials for Smart Multifunctional Superstructures* [*(MS)^2*], FY18-22
- *Advanced Optical Materials that Create Force from Light,* FY18-22
- *In situ Microstructural and Defect Evolution below the Micron Scale in as-Deposited Metal Alloys,* FY18-22
- *Predicting and Validating Pathways for Chemical Synthesis,* FY18-22
- *Phase Change Materials for Photonics,* FY17-21
- *Dynamic Events at Ultra High Temperature and* Pressure, FY17-21
- *Physics, Chemistry and Mechanics of Polymer Dielectric Breakdown,* FY17-21
- *The Science of Entropy Stabilized Ultra-High Temperature Materials,* FY16-20
- *Metalloid Cluster Networks,* FY15-19
- *Computational and Experimental Methods towards Understanding the Chemistry and Physics of Materials >2000°C,* FY15-19
- *Exploring the Atomic and Electronic Structure of Materials to Predict Functional Material Properties,* FY14-18
- *Understanding Energy Harvesting Mechanisms in Polymer-Based Photovoltaics,* FY14-18
- *Replacing Strategic Elements in DoD Materials,* FY13-17
- *A New Way to Dissipate Shock Wave Energy from Detonations,* FY12-17
- *Biological Stability of Future Naval Fuels and Implications for the Biocorrosion of Metallic Surfaces,* FY11-17
- *Atomic-scale Interphases: Exploring New Material States,* FY11-17

BRC:

A Scientific Basis for Enhanced Manufacturability with Electrical Currents, FY17-20