National Aeronautics and Space Administration

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Overview of Advanced Materials for Rotorcraft Engines and Drive Systems

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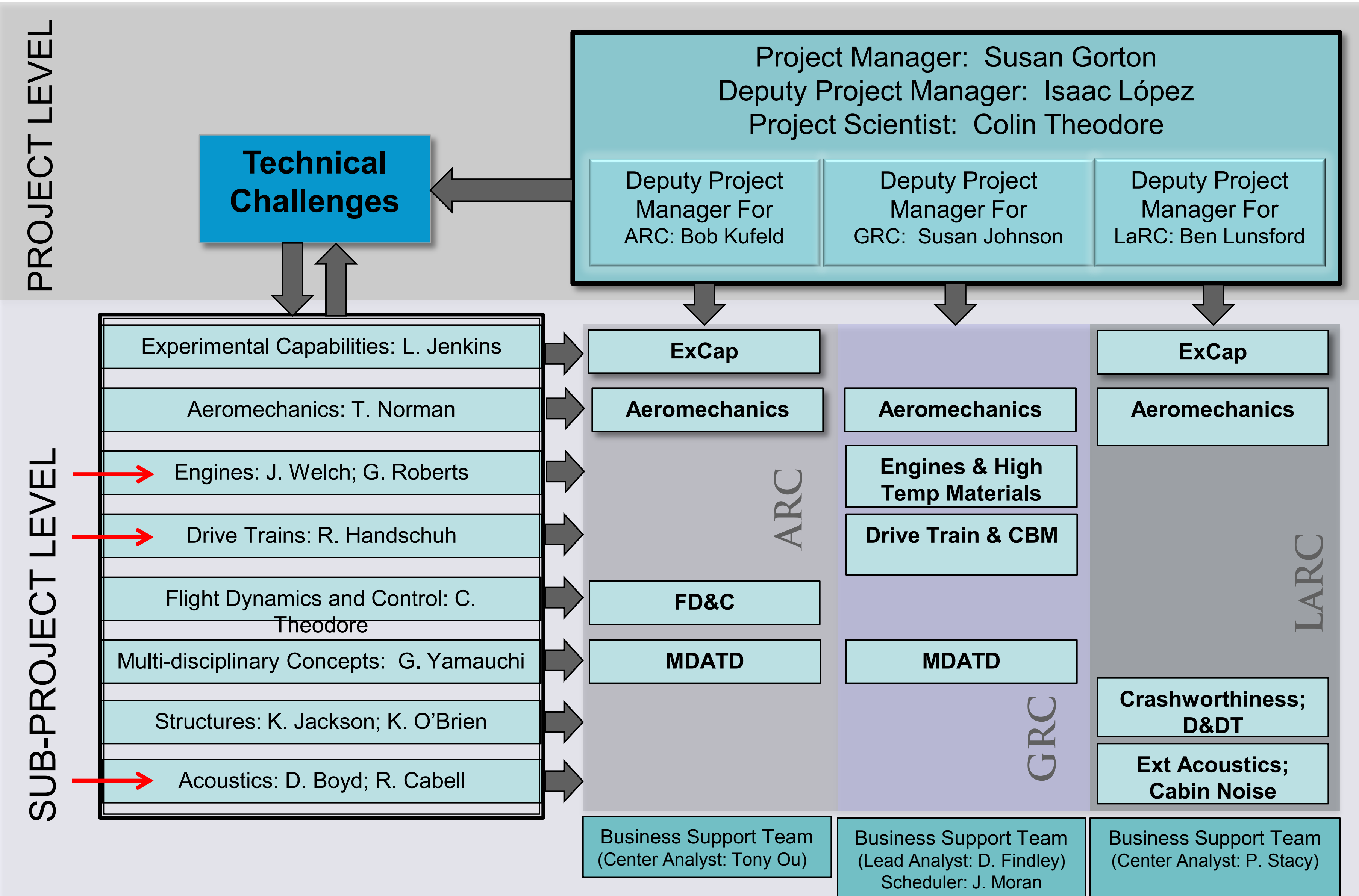
SRW Project Organization



Overview

- Engine materials
  - Update on engine cycle studies
    (POC: Dr. Robert Bruckner)
  - Erosion resistant thermal barrier coatings (TBC’s) for turbine blades
    (POC: Dr. Robert Miller)
  - Ceramic matrix composites (CMC’s) for turbine vanes and blades
    (POC: Mr. Michael Halbig)
- Drive system materials and structures
  - Composite material applications
    (POC’s: Mr. Lee Kohlman; Mr. Charles Ruggeri)
    - Hybrid metal/composite gear
    - Dynamic test method development
  - Super-elastic alloy for bearings
    (POC: Dr. Christopher Dellacorte)

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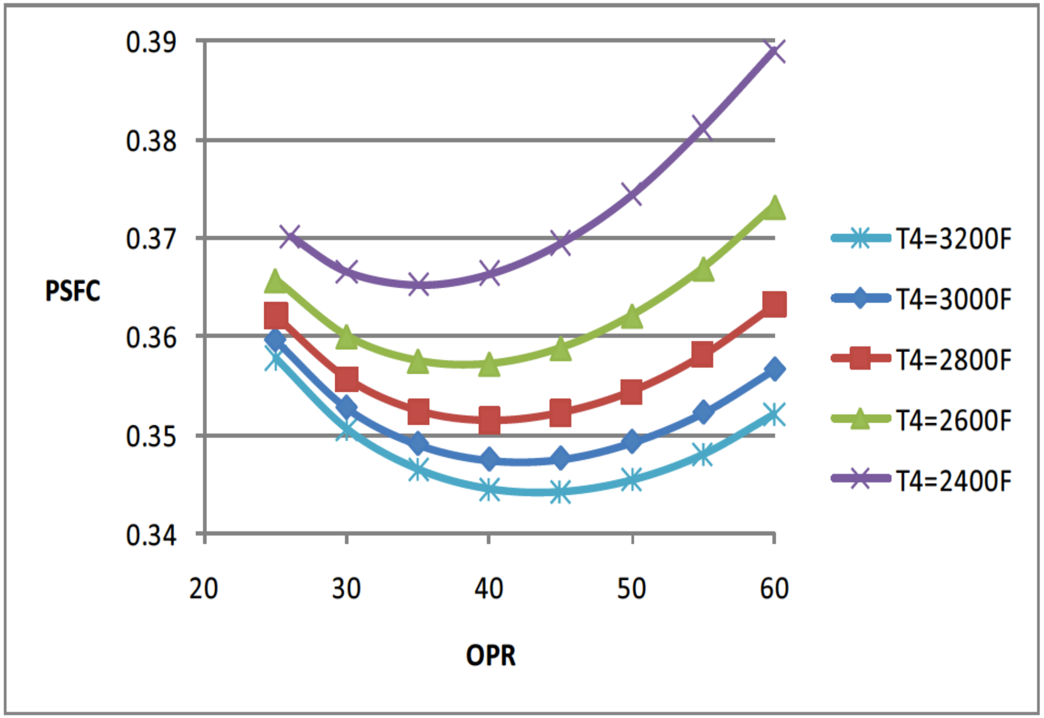
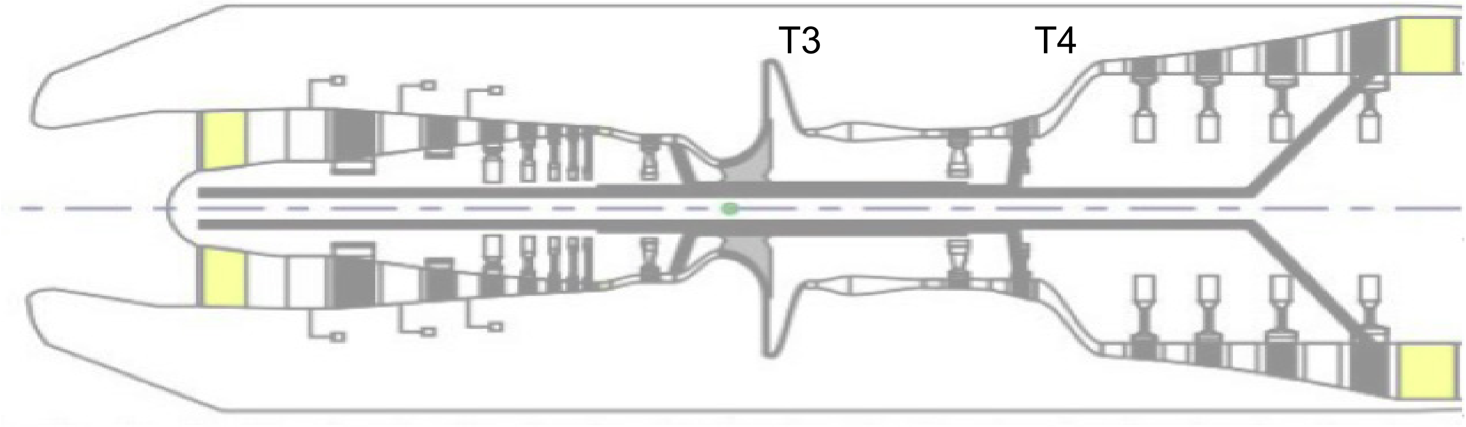
Engine cycle studies

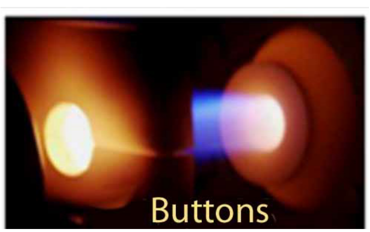
- Current work on TBC's and CMC's addresses the need for higher T4
- Recent studies indicate that fuel burn continues to improve with OPR ~45 and T4~3200.
- Impeller technologies needed to achieve the required OPR (higher T3) are being considered

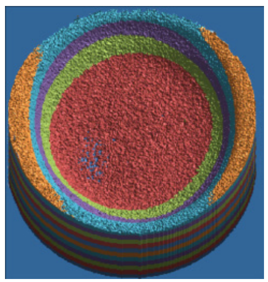


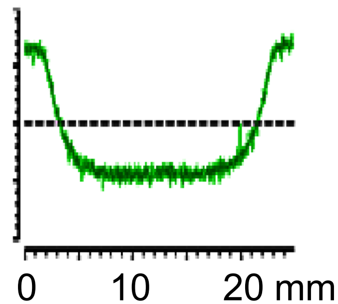


Erosion resistant thermal barrier coatings

- New TBC's can enable an additional 200ºF (111ºC) increase in surface temperature compared to current TBC's, but erosion and impact resistance become a greater issue
- Goal is to improve erosion resistance of coatings and demonstrate performance of the new coatings in future engine tests (SRW project demo tests or industry collaborations)







FY11 accomplishments

- Improved burner rig design produced a more uniform erosion area in button specimens
- 4 new TBC's were down-selected for further work (see next chart)
- A roadmap was developed to take advantage of possible future engine test opportunities

Data needed before future engine qualification tests

- Erosion tests with high fidelity rig
- Impact (rig under construction)
- Furnace cyclic life
- High heat flux performance
- Thermal conductivity

Erosion resistant thermal barrier coatings

Process/Composition	Improvement	Comments
EB-PVD Process		**SOA deposition approach**
Zirconia-yttria baseline	1X	SOA composition
Zirconia-yttria-gadolinia-ytterbia (3 composition- 6 process-variations)	1.3-1.5X	Lower conductivity/higher temperature capability
Zirconia-yttria-titania-tantala (2 comp. variations)	0.5X	Higher tougness; harder to deposit
Directed Vapor Process		**Promising newer process**
Zirconia-yttria baseline	1X	SOA composition
Zirconia-yttria-gadolinia-ytterbia (3 variations)	2X	Lower conductivity/higher temperature capability
Zirconia-yttria-gadolinia-ytterbia -titania-tantala (5 variations)	2X with scatter	Somewhat easier to deposit
Plasma Spray-PVD Process		**New process (low TRL), but complex composition potential**
Zirconia-yttria	Low resistance	
Zirconia-yttria-gadolinia-ytterbia	Low dep. to date	
Selected for further study		

Composition:

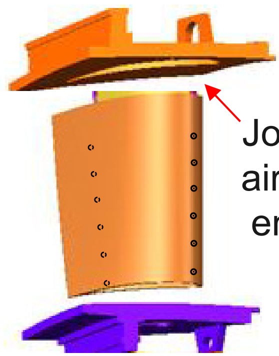
- Current TBC's are 2 component
- 4 component coatings have improved erosion resistance with lower thermal conductivity
- 6 component coatings should be tougher (Ti and Ta additions), but are harder to deposit by vapor deposition techniques (vapor pressure differences)

Process:

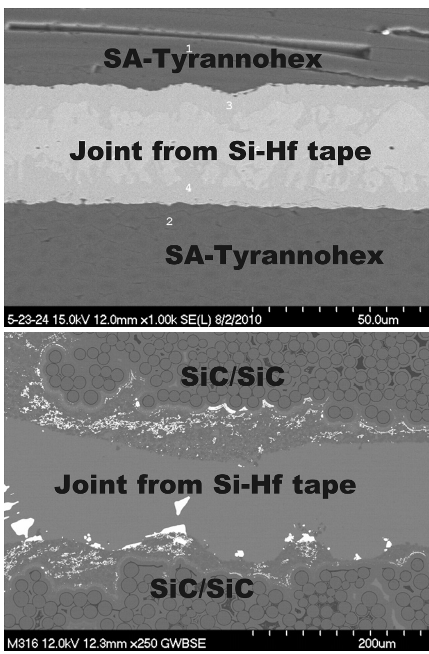
- EB-PVD is the baseline process
- Directed vapor process has shown promising results for 4 and 6 component compositions
- Plasma Spray-PVD has potential, but is currently at low TRL

Ceramic matrix composites (CMC's)

Joining of Vane Segments



Joint Microstructures



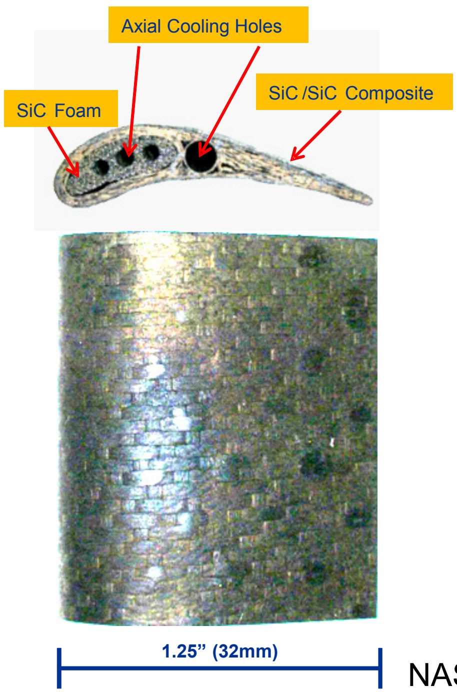
Joining Performance Requirements

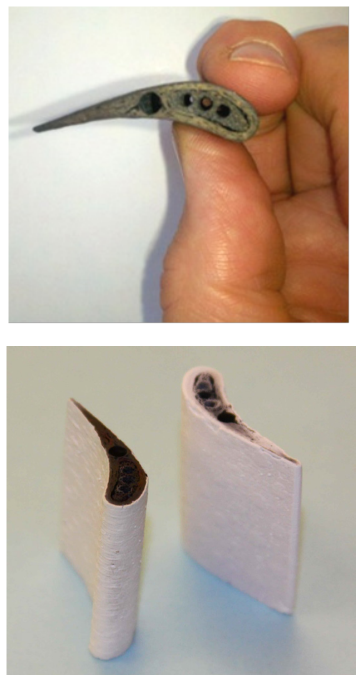
- Strength of 25 Mpa
- Temperature capability to 1200ºC
- Uniform and leak free bonds
- FT11 Accomplishments
  - – Joining approaches developed
    - Diffusion bonding with Ti and B-Mo metallic foils
      - – Good bond quality - but requires use of a hot press and flat geometries
    - Brazing with eutectic phase powders (Si-Cr, Si-Ti, and Si-Hf)
      - – Paste interlayers gave non-uniform bonds with gaps/voids
      - – Developed a green tape interlayer for brazing (Si-Hf) which gave very good bonds. Approach down-selected.
  - – Shear strength tests at R.T. and elevated temperatures conducted

		ROOM TEMP	750° C	1200° C
Substrate	Number of Si-Hf Tape Layers	Average Apparent Shear Strength, MPa	Average Apparent Shear Strength, MPa	Average Apparent Shear Strength, MPa
⊥SA - Tyrannohex	1	95.2 (±18.7)	65.6 (±3.4)	75.7 (±13.8)
⊥SA - Tyrannohex	2	102.1 (±15.9)	70.9 (±5.2)	56.9 (±12.1)

Ceramic matrix composites (CMC's)

Fabrication Ability of Small CMC High Pressure Turbine Vanes
Concept #1 – Internally Cooled Vane





NASA environmental barrier coating applied

- Airfoils fabricated by Hyper-Therm High-Temperature Composites, Inc.
  - Material details: two sets of SiC/SiC airfoils with Sylramic and Hi-Nicalon-S SiC fibers, CVI SiC matrix, and SiC foam core
- Challenges include:
  - Fabrication of a small airfoils: 1"x1" (vane cord length x height)
  - Internal cooling schemes and external film cooling
  - High inter-laminar strength and robust leading and trailing edges.
- Planned testing
  - High pressure burner rig
  - Laser high heat flux thermal gradient rig

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Hybrid gear fabrication at A&P Technology

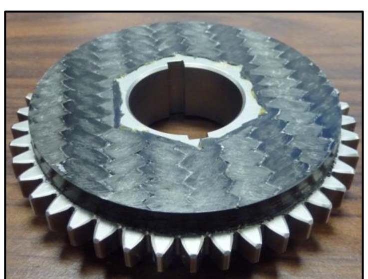
Baseline metal spur gear

- 12 pitch spur gear (42 teeth)
- AISI 9310 gear steel
- 25 degree pressure angle
- 3.5'' pitch diameter
- ¼'' face width

0.8847 lb

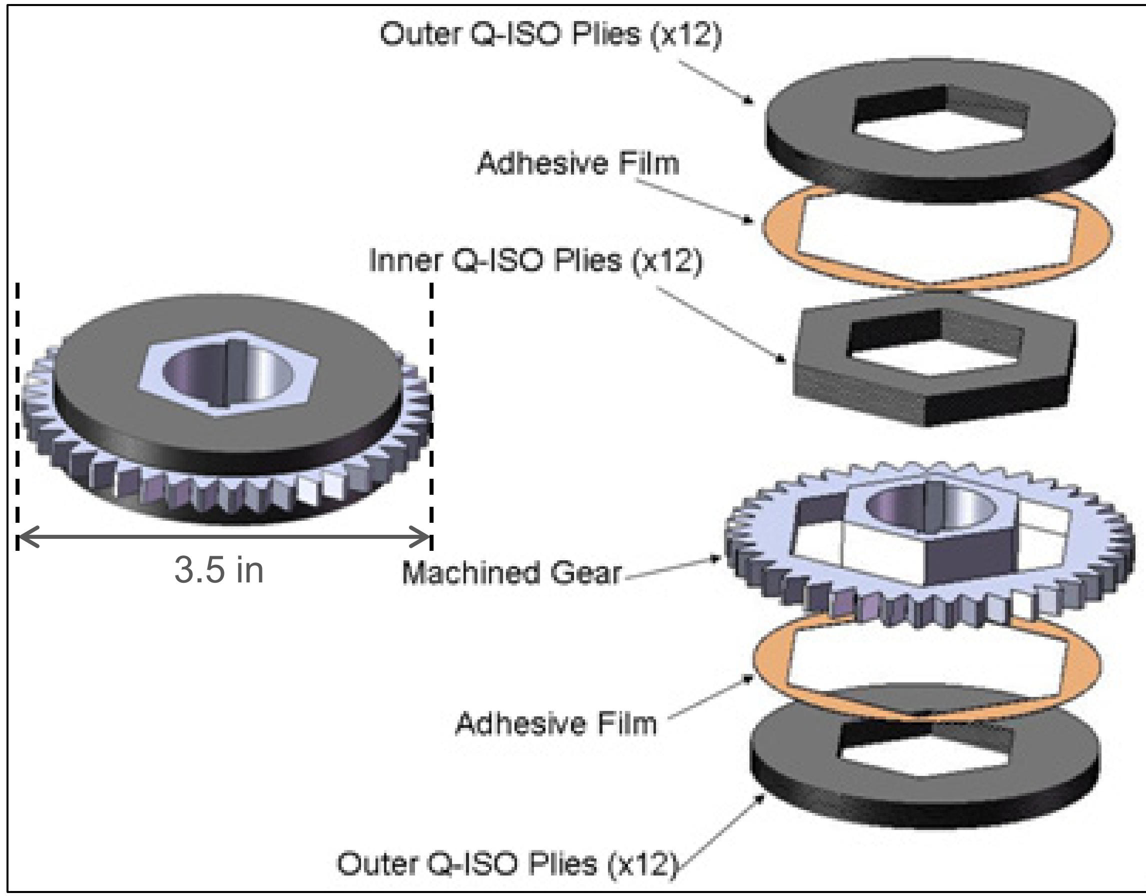
Hybrid gear

(NASA patent pending)



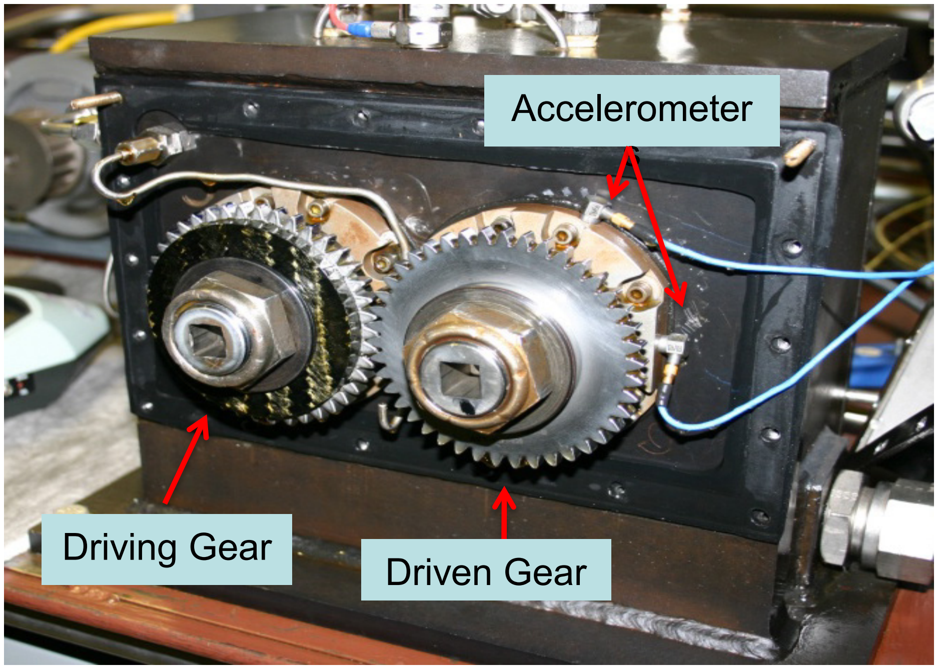
0.7081 lb
(22% reduction)

- Contract completed to fabricate small test gears
- New SBIR Phase 1 contract awarded for larger gears

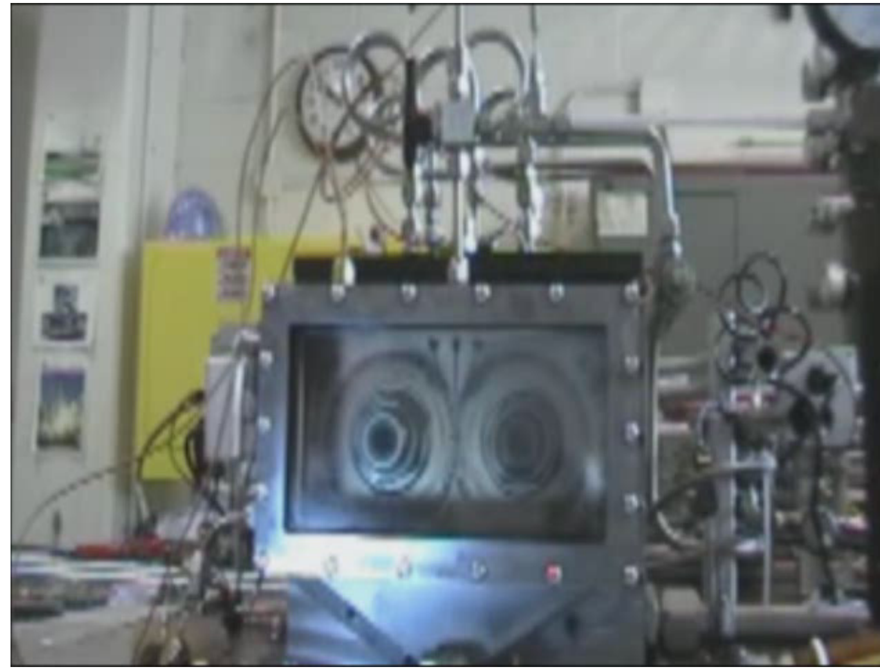


Hybrid gear testing at NASA

Spur gear test rig



Loss of oil test (steel gears)



Current test results

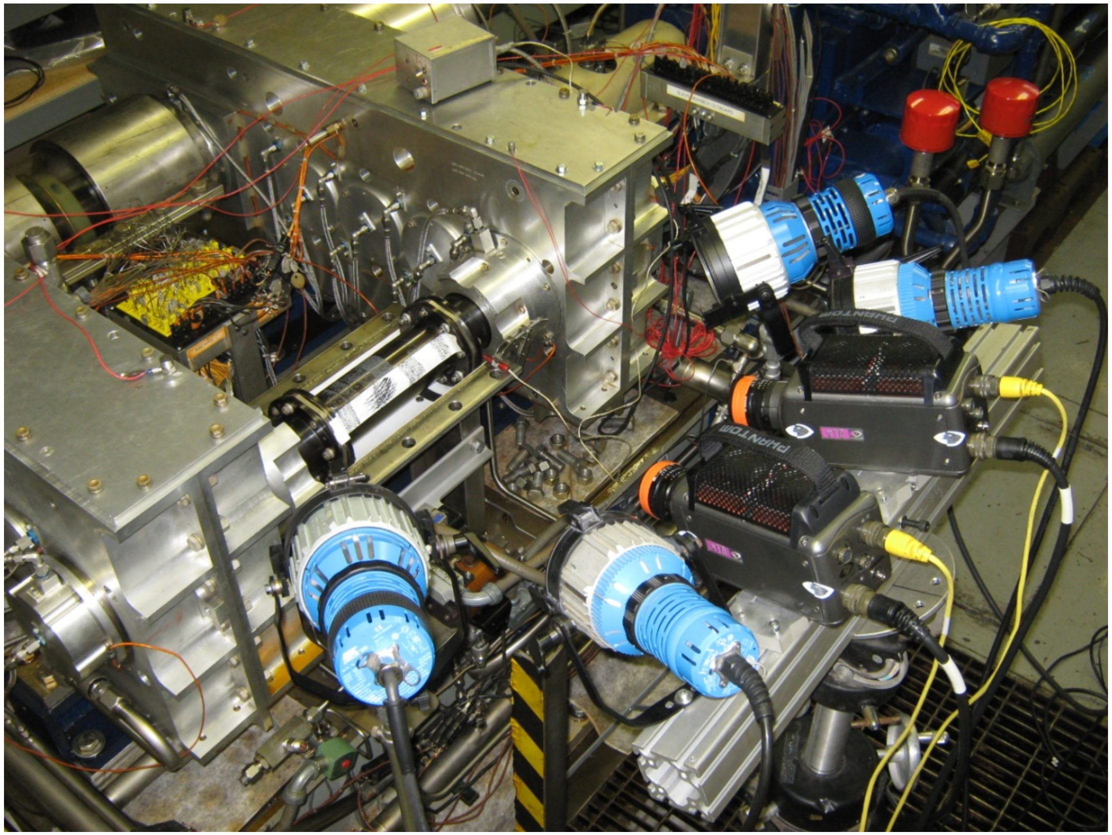
- 300×10^6 cycles, 553 in-lb torque, 10,000 RPM with no damage
- Possible noise and vibration reduction
- Detailed results to be presented (Handschuh et al., AHS Forum, May 1-3, Ft Worth, TX)

Future plans

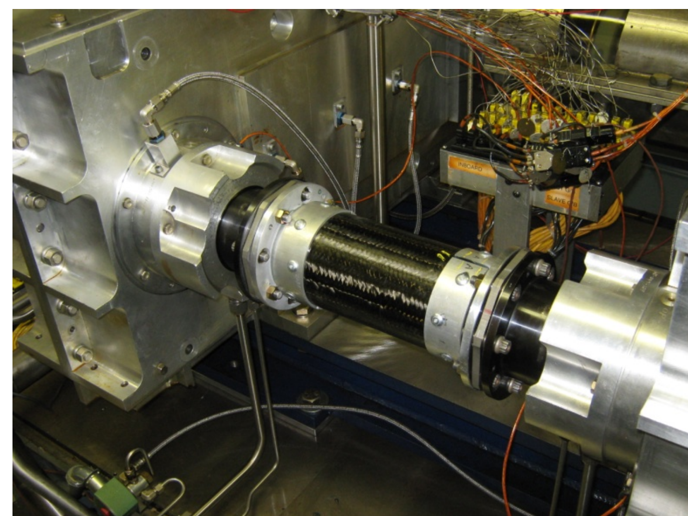
- Endurance testing to 10^9 cycles
- Torque overload
- Single tooth loading
- Loss of oil
- Large gears

Dynamic test method development

Shaft used as a test article in a closed loop gear test rig

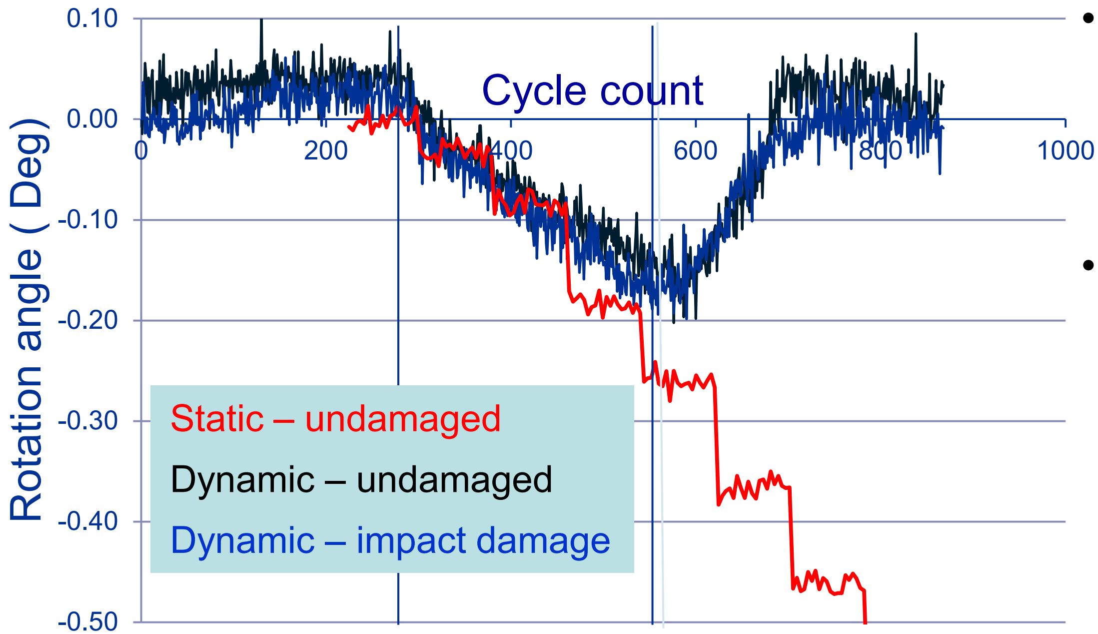


- High speed cameras are triggered to capture multiple images per revolution
- Digital image correlation is used to measure deformation
- Pulsed lighting approaches are being developed for better time and spatial resolution



- Detailed results to be presented
  (Kohlman et al., AHS Forum, May 1-3, Ft Worth, TX)

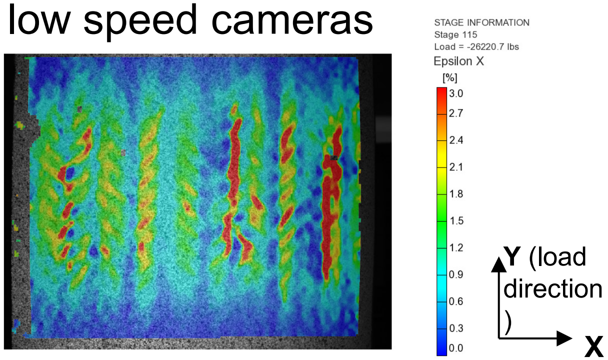
Angular displacement measurements



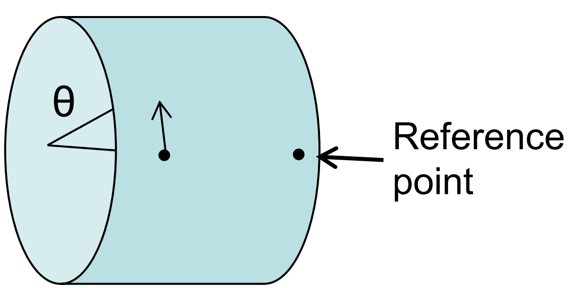
RPM 0 ⟶ 5,000 ⟷ 5,000 ⟶ 0

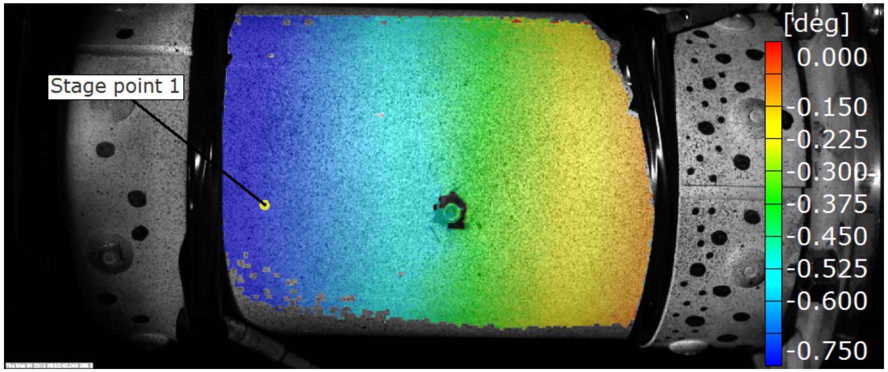
Torque (in-lb) 0 ⟷ 0 ⟶ 10,000 ⟶ 0 ⟷ 0

- Currently working to reduce noise and improve resolution (shutter time, light intensity, lens aperture, pulsed lighting, field of view, static reference)
- Goal is to measure local deformation at resolutions similar to previous work with low speed cameras



Strain pattern during a pressurization test observed with low speed cameras



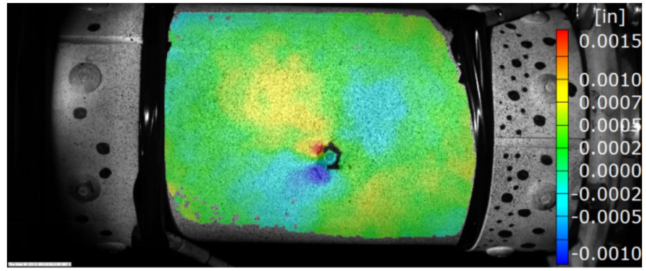


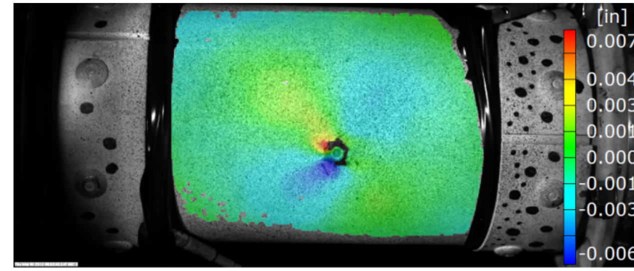
Deformation near impact damage

10,000 in-lbs | 38,000 in-lbs

Radial displacement

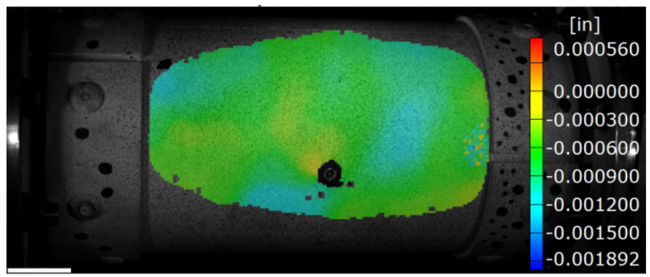
Static





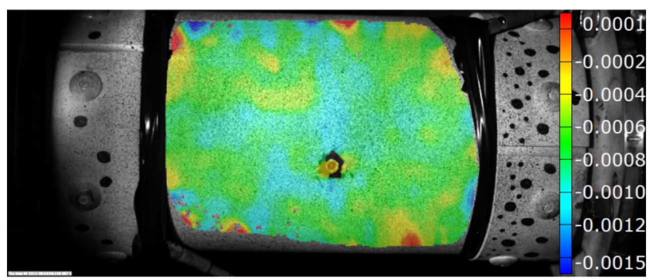
+0.0073 in max (red)
- 0.0030 in min (blue)

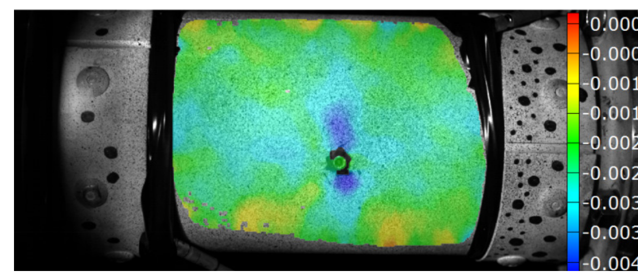
Dynamic
(5,000 RPM)



In-plane shear (ε_{xy})

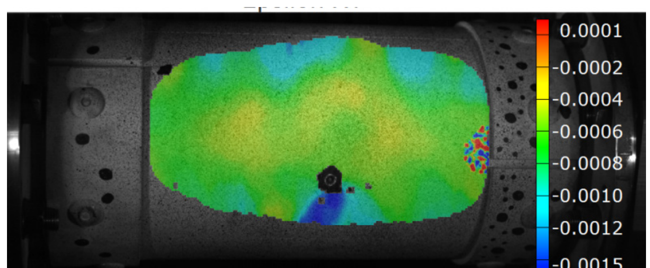
Static





0.0042 max shear strain
near impact damag site

Dynamic
(5,000 RPM)



Need better resolution and data analysis algorithms (blue spot is a result of edge effects and calculation method)

Super-elastic bearing material - NiTiNOL

- Material
  - Non-ferrous intermetallic, 60NiTi (60wt% Ni + 40wt% Ti)
  - Invented by W.J. Buehler (late 1950's) at the Naval Ordinance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordinance Lab)
  - Similar composition to 55NiTi shape memory alloy
- Key material properties
  - 15% lighter than steel
  - Super-elastic (high elastic strain to failure, low modulus)
  - High hardness
  - Corrosion resistant
- Potential benefits for bearing performance
  - Lighter weight
  - Higher power density
  - Higher transient load capability
  - Debris tolerant

Super-elastic bearing material

- Some critical bearing material requirements
  - High hardness (>Rockwell C58)
  - Wear resistant and compatible with existing lubricants
  - Resistant to rolling contact fatigue (RCF)
  - Capable of fabrication into ultra-smooth surfaces
  - Dimensionally stable and easy to manufacture

	NiTi-60	NiTi-55	440C	M-50
Density (g/cm^3)	6.7	6.5	7.7	8.0
Hardness (HRC)	56-62	35-40	58-62	60-65
Young's modulus (Gpa)	95	100	200	210
Fracture toughness ($MPa/m^{½}$)	TBD	TBD	22	20-23

High hardness, low modulus, and high elasticity for NiTi-60are an unusual combination of properties that could resulting in improved bearing performance

Super-elastic bearing material

- Accomplishments for FY11
  - Demonstrated 60NiTi and 61 NiTi hardness >62 HRC using heat treatment above 900ºC
  - Ongoing investigation of processing methods to achieve a fine microstructure and minimize precipitates
  - Performed fabrication trials for bearing smooth, round, straight rods for measurement of rolling contact fatigue (RCF)
    - RCF data is critical to evaluate use in highly loaded, high speed, long duration bearings

NASA