Concept for Determining the Life of Ceramic Matrix Composites Using Nondestructive Characterization Techniques

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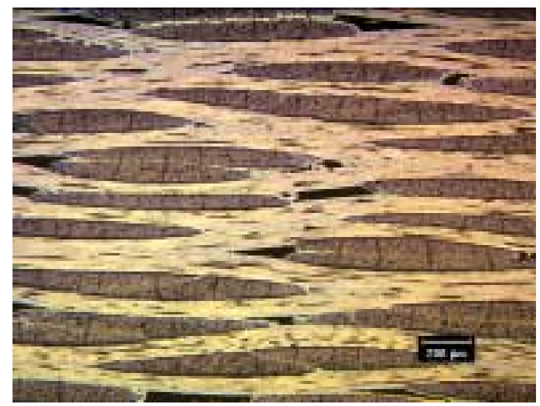

4th Conference on Aerospace Materials, Processes, and Environmental Technology
Von Braun Center, Huntsville, Alabama,
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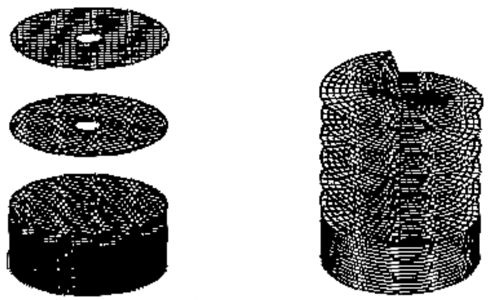
Agenda

- NDC Life Determination Background
  - Simplex Turbopump CMC Blisk NDC Data
  - Tensile Specimen Test Data
- General NDC Life Determination Concept
- Potential for Concept
- Case Scenario
- Challenges
- Justification
- Summary

Background

- Simplex CMC blisk program initiation in 1995
  - Two C/SiC integrally bladed disk (Blisk) architectures tested:



Quasi-isotropic Polar

- Thought process relative to Nondestructive Characterization (NDC) usage:
  - Try to use damping to monitor blade damage accumulation
    - Resulted in Argonne National Laboratory contracted to conduct damping and computed tomography analysis in as-received, post-proof testing, and post-turbopump testing states
    - 1998 results from as-fabricated to post-proof indicated changes were detectable
  - Formulated NDC Life Determination concept in 1999

Damping and Resonant Frequency Testing Data

- Simplex Blisk
  - Argonne National Laboratory tested:
    - As-fabricated, post-proof, and post-turbopump test conditions
  - Southern Research Institute tested:
    - Post-proof, and post-turbopump test conditions

- Coupon Specimens--establish baseline behavior for NDC C/SiC for different stresses

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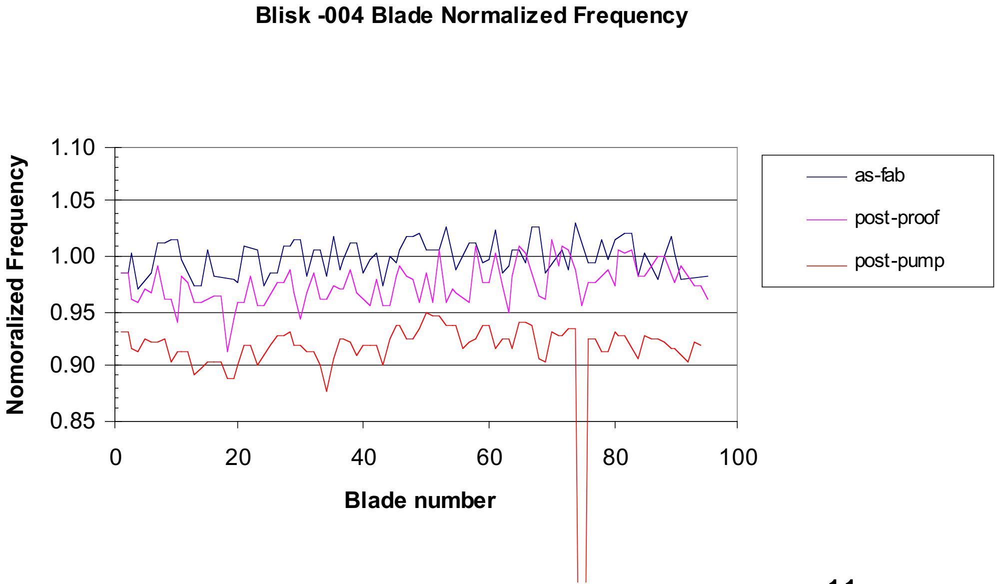
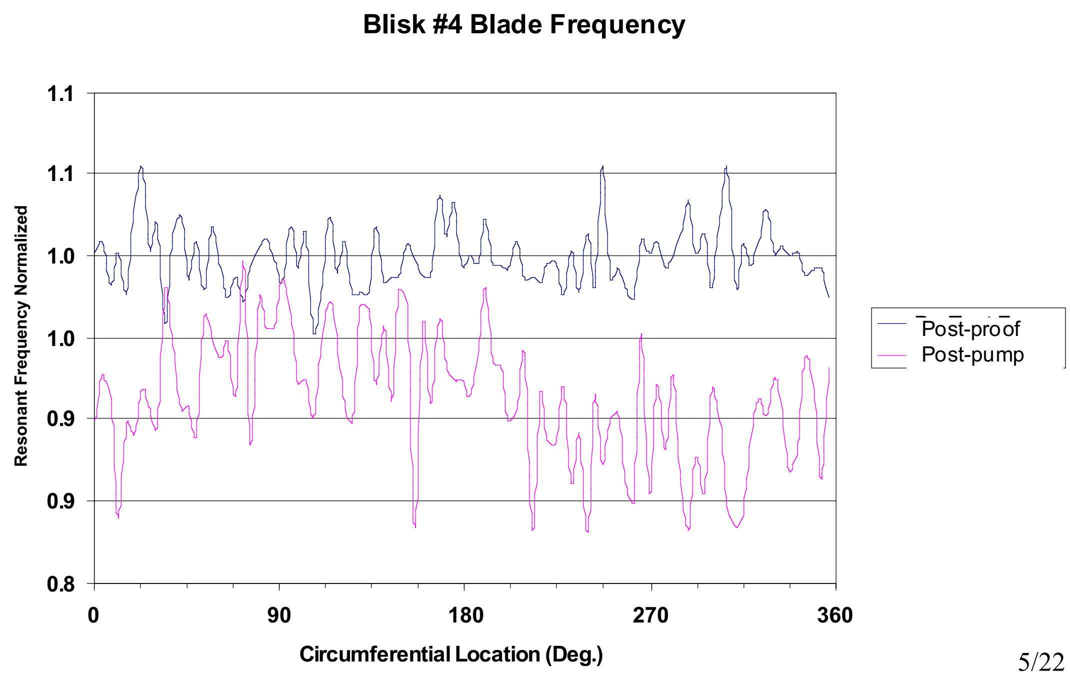
Blade Resonant Frequencies

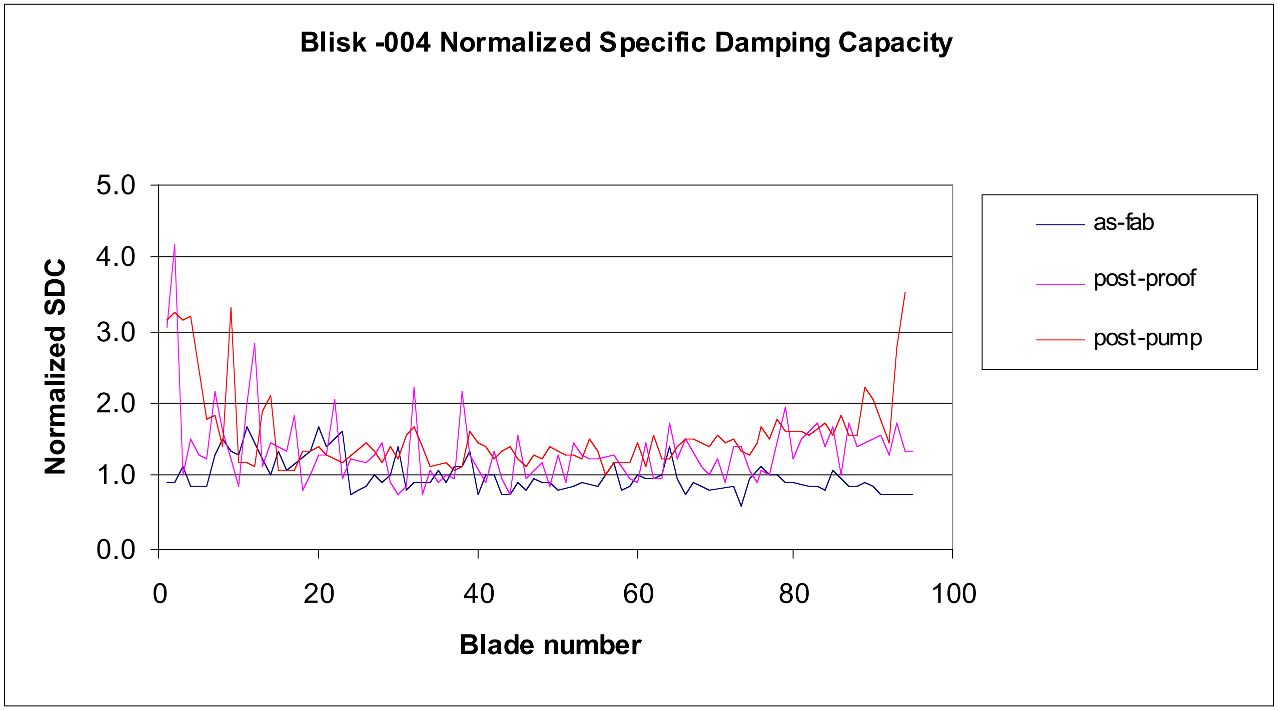


ANL Examined
Range 1

SRI Examined
Range 2



Specific Damping Capacity



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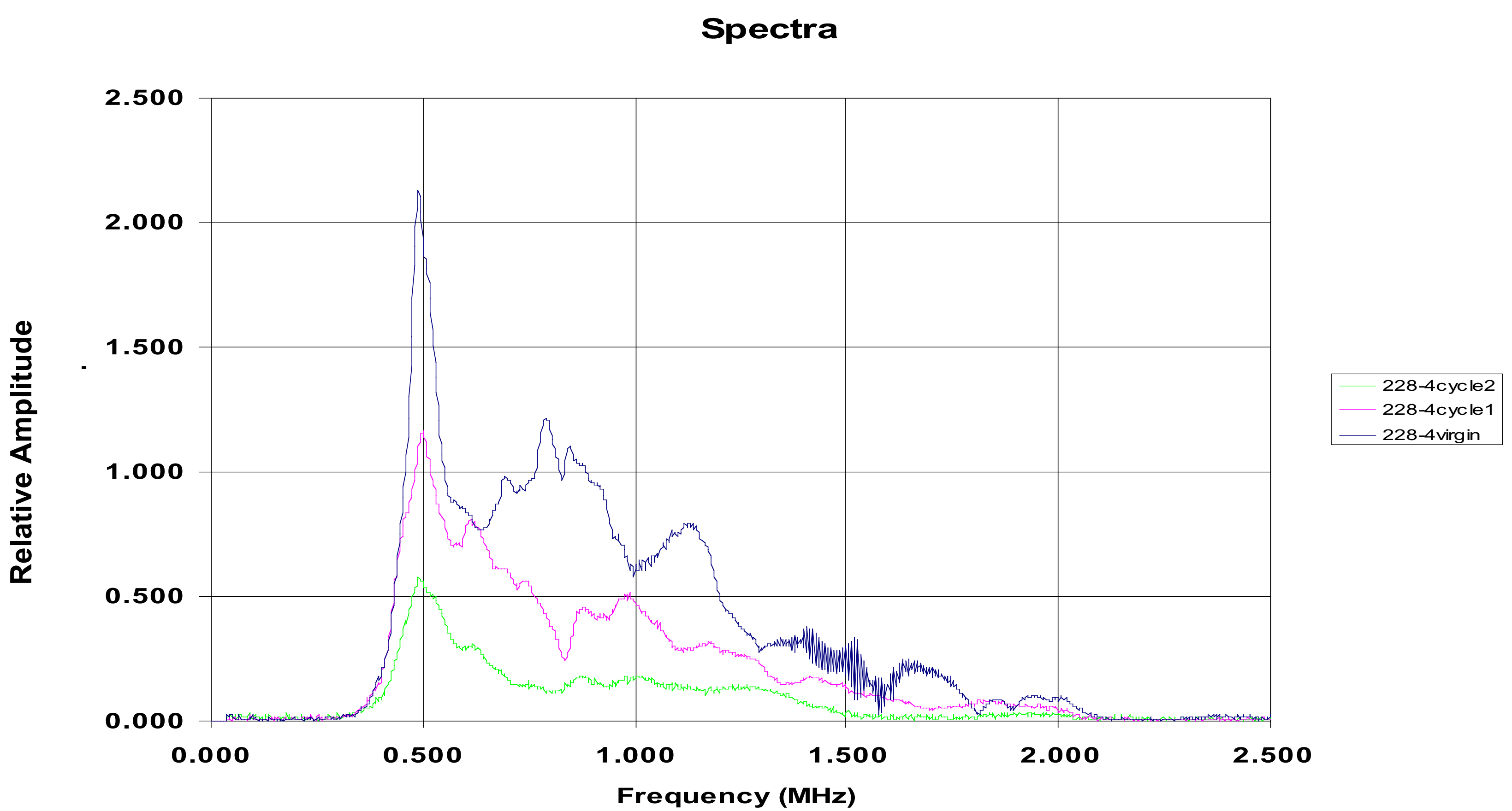
Ultrasonic Spectroscopy Coupon Data



- DAMAGE MONOTORED BY SONIC VELOCITY, RESONANCE AND AND ULTRASONIC SPECTROSCOPY
- INCREASING DAMAGE SEEN WITH HIGHER LOAD LEVELS

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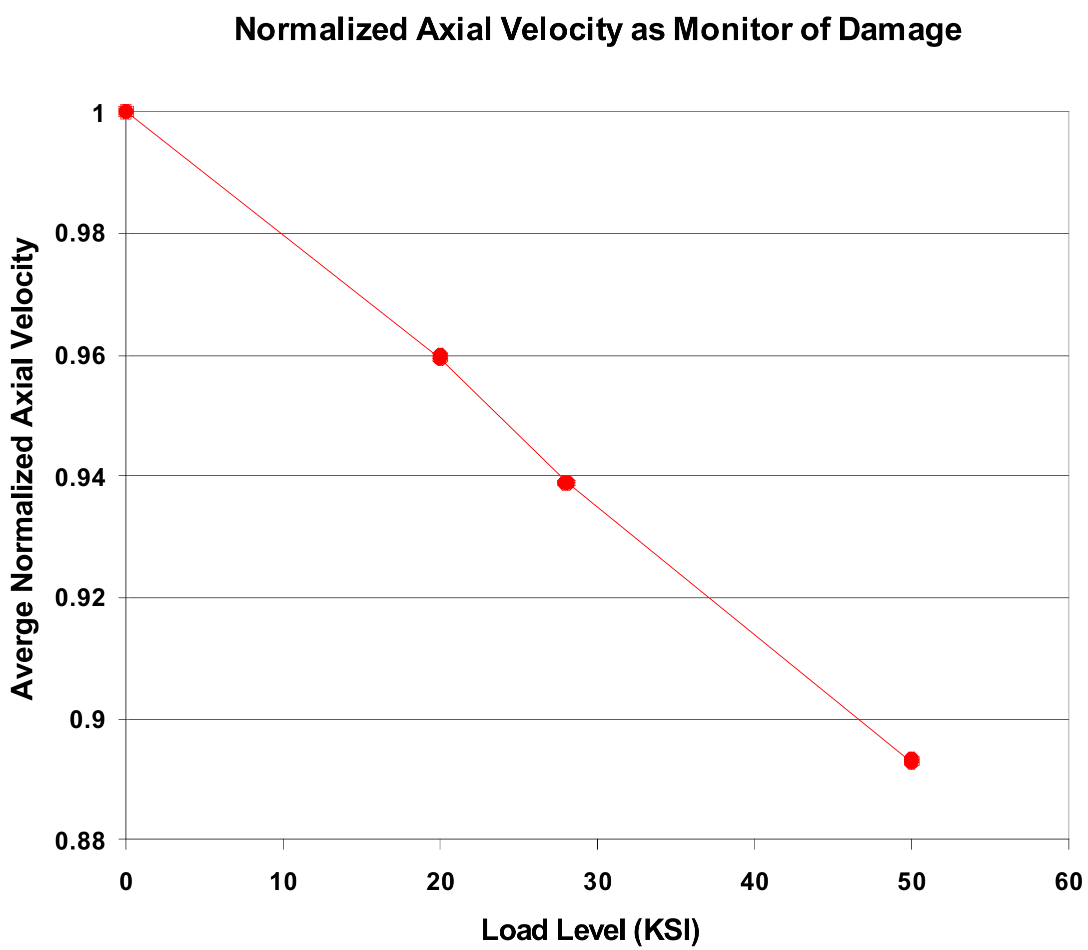
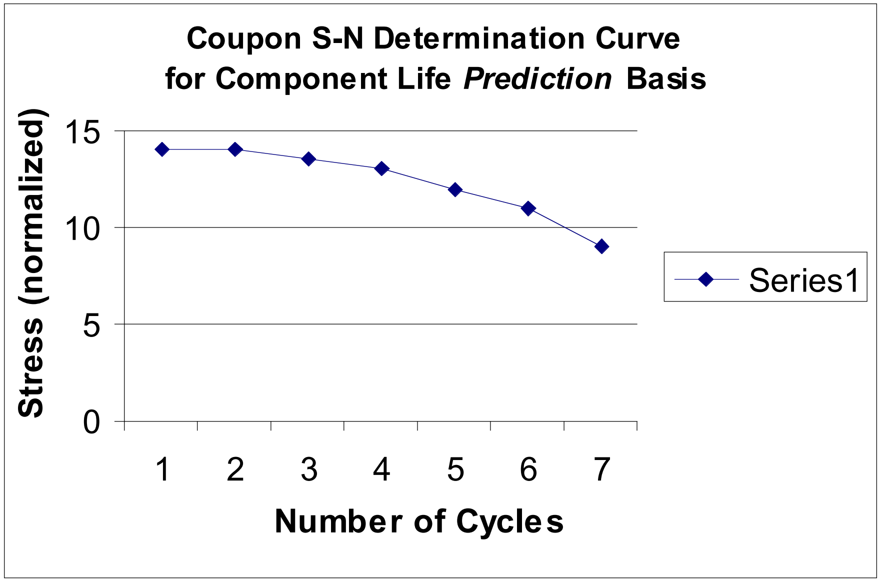
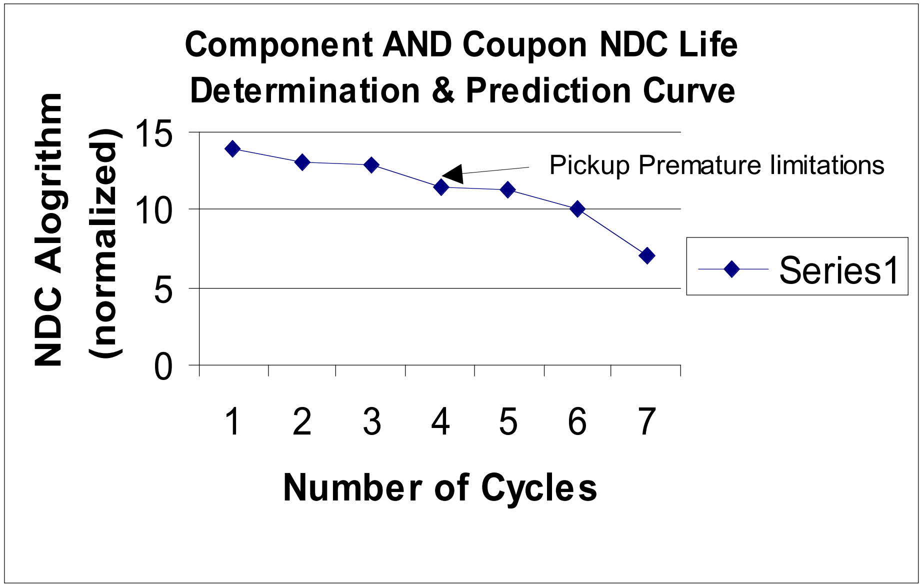
Axial Velocity Coupon Data



Ideal Goal

Old Way → New Way in Future





- NDC algorithm consist of:
  - Original Material Quality:
    - Computed Tomography (density/fiber architecture map), conventional coupon property baseline, NDC degrading baseline data
  - Degrading material properties and characteristics consist of:
    - Specific diffusivity, temperature capability (composition), density, strain, geometry, damping capacity, resonant frequency, modulus, etc.

Potential Payoff

- Increase Safety and Decrease Costs
  - Real-time life determination of component (not predicted)
    - Know component's integrity and health condition at any point in time.
    - React/respond real-time to FOD, overstress, and similar type events
  - Degraded residual life prediction (i.e. forecast) for component
    - Don't retire component prematurely
    - Don't conduct unnecessary disassembly inspections (thus decrease wear on other components and decrease turnaround time and cost)
    - Know that FOD & overload events may decrease life x%
  - Integrate health monitoring and control units into one control system--translates in to weight and complexity savings

Phenomena that are Necessary to be Accounted For:

- Mechanical
  - Initial inelastic strain
  - Progressive inelastic strain
  - FOD
  - Fatigue wear of fibers and matrix
  - Off nominal stress exposure
- Environmental
  - Thermal Shock
  - Oxidation
  - Erosion
  - Surface chemistry
- Combined Mechanical and Environmental Conditions
  - Creep/stress rupture (aka stressed-oxidation)
  - Thermal Mechanical Fatigue

Possible Means to Account for Real-time events

- Possible real time detection devices and quantifiable data:
  - Lasers
    - strain, emissivity, temperature, FOD events, dimension changes, off gassed particle velocity, species and amounts
  - Thermography
    - specific diffusivity, density, crack growth
  - Vibro-acoustics
    - specific damping capacity, resonant frequency, modulus
  - Optics
    - FOD events, dimensional changes, temperature
  - Sensors (strain, thermocouples, pressure, surface mount, remote, embedded, existing health monitoring data, etc.)
    - strain, modulus, temperature, on-set of corrosion, electrical resistivity

Specific Technique Data Gathering Already Demonstrated

Means of Detection	Detectable Data and Events Claimed in Abstracts	Source/Reference
Acoustic emission	Real-time CMC damage correlated to load/unload stress-strain	Luo, Jyi-Jiin, et. al. Rev, of Prog. Quant. NDE, 13A, 1994.
Acousto-ultrasonic	Real-time fatigue damage	Tiwari, Anil et. al., Nondes. Char. Of Mater., Jan 1994
Electro-optical biaxial displacement follower	Real-time displacement, velocity, acceleration	Optometrix, West Haven CT
Impact Acoustic Resonance	Specific damping capacity	Shiloh,K et. al, Trends in NDE Sci. Tech., Jan 1997
Acoustic Resonance-Modal analysis	Resonant frequency	Papazoglou, V.J., et. al., Applied Comp. Materials, 3, 1996.
Embedded Sapphire Fibers	Structure (?)	El-Sherif, Mahmound et. al, Nond. Eval. Of Mtls. and Comp. Dec. 1996
Impact Acoustic Resonance	Porosity	Shiloh,K et. al, Trends in NDE Sci. Tech., Jan 1997
Impact Acoustic Resonance	Interlayer fiber orientation	Shiloh,K et. al, Trends in NDE Sci. Tech., Jan 1997
Pulse echo ultrasonic Time-of-flight	Microstructural gradients (pore fraction, density, fiber fraction, chemical variations)	Roth, Don, Mater. Eval. 56,9, Sept, 1998.
Ultrasonic	Stress-strain curve reconstruction	Baste,Stephane, et. al. Jan 1996, J of Comp. Mtls.
Pulse-echo thermal wave	Density and disbonds	Khandelwal,P. et al, 21st Ann. Conf. Comp., Adv. Cer., Mtls. & Struct.-B, 1997
Air-coupled ultrasound & Thermography	Delaminations and density gradients	Pallai, T.A. et. al, 21st Ann. Conf. on Comp. Adv. Cer., Mtls., & Struct.—B, 1997
Laser Speckle	Strain & displacement	Dixon,G.J., Laser Focus World, June 1998

Specific Technique Data Gathering Already Demonstrated (con't)

Means of Detection	**Detectable Data and Events Claimed in Abstracts**	**Source/Reference**
X-ray Diffraction	Residual stresses	Proto Inc., Detroit MI
Resonant frequency	Bulk and shear moduli, and poison's ratio	Quatrosonics, Inc., Albuquerque, N.M. (Am. Cer. Soc. Bul, 74, 11, Nov. 1995)
Ultrasonics	9 stiffness coefficients	Baste, Stephane, Rev. of Prog. In Quant. NDE, 1995
Dynamic mechanical resonance	Thermal Shock (crack damage)	Singh, Raj, et. al. Trends in NDE Sci Tech., Jan 1997
Resonant Ultrasound Spectroscopy	Thermal Shock (crack damage)	Singh, Raj, et. al. Trends in NDE Sci Tech., Jan 1997
Laser	Emissivity	The Pyrometer Inst. Co.
Ultrasonics	Oxidation (flow rates & temps)	Chu, Ya-Cherng, et al. Am. Cerm Soc., 78,7, Jan 1995
Ultrasonics	Oxidation (time, temp, and flow)	Chu, Y et. al. Rev. of Prog in Quant. NDE, 13B, 1994.
Differential Thermography	Crack progression	Camden, M.P. et. al., 5th Inter. Conf. on Comp. Enger., July, 1998
Electrical	Electrical resistance	Maile,K. et. al, 5th Inter. Conf. on Comp. Enger., July, 1998

Modeling Using NDC data

- "Disturbed State Constitutive Modeling Based on Stress-strain and Nondestructive Behavior,"
  - Desia, Chandra et. al, Int. J of Solids and Struct. 33,11, 1996. (predict remaining life)

- "Modeling Mechanical Response of SiC/CaS-II Ceramic Composite under Quasi-Static Loads using a Real-Time Acousto-Ultrasonic NDE Technique,"
  - Tiwari, Anil et. al, J of Comp. Mtls., 29,13, 1995.

NDC Life Determination Scenario

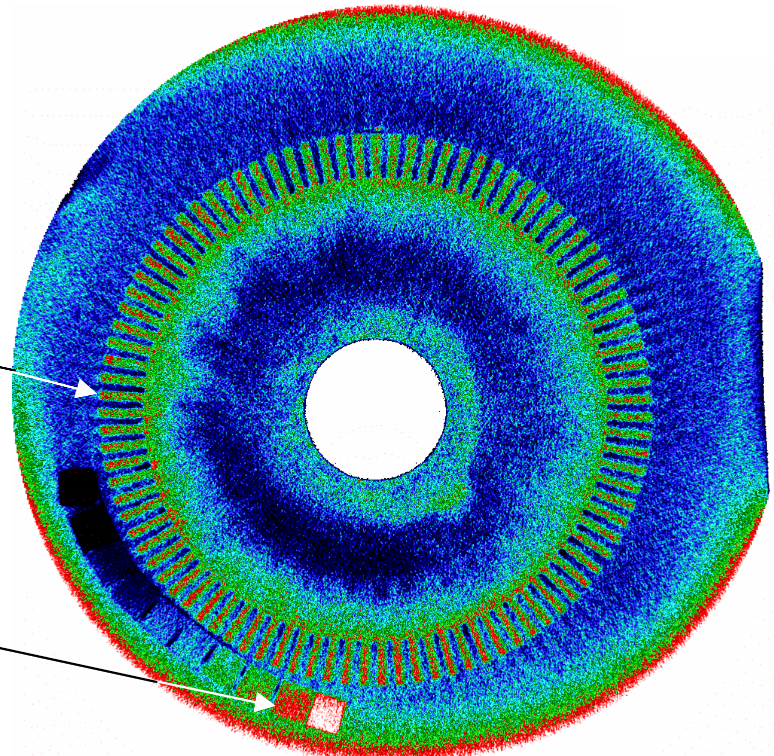
- Baseline NDC data with laboratory coupon data.
  - Ultimate strength/strain of materials, etc./extrapolate with micromechanics
- Establish state of material with CT and thermography
  - I.e. map density, actual processed geometry (could be a little different than design), and specific diffusivity
- Overlay material properties on CT map as function of density, preform, compositional specifics, etc.
  - Could have functionally graded preform of fibers and/or matrix
- Overlay inhibited matrix requirements
- Overlay different event scenarios discretely on image
  - Failure scenarios at a turbine blade root and blade edge are different
- Use real time techniques to monitor damage accumulation progression and events.
- Couple events monitored with NDC to discrete algorithms in model to determine life and residual life of the component

Scenario

Where Computed Tomography is now calibrated to determine density, calibrate it in the future such that other NDC data, coupon property data, and degradation/damage event scenarios can be discretely mapped on to each layered image. This could be the basis of the NDC Life Determination model. As NDC properties are fed into the model real-time, then the component lifetime adjusted as appropriate.

High density indicated by C/C density blocks currently.

In future, the red could indicate mechanical fatigue of 1 million cycles after reducing NDC data on to the CT file.



Polar C/SiC blisk prior to tubopump testing

Challenges

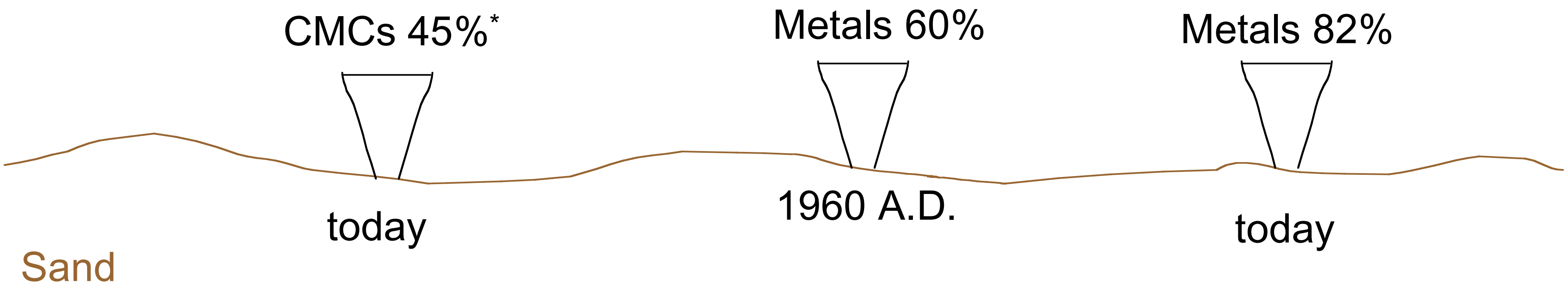
- Detecting all types of material degradation
  - Might not have NDC tools to detect all means of degradation
- Distinguishing between different types of degradation
  - e.g. If thermography is used, then is the change in signal from oxidation of the surface layer or microcracking
- Developing an algorithm which accurately reflect all aspects of CMC life
- Miniaturization of NDC equipment for flight hardware
  - Some equipment might not be feasible for flight
- Case, E.D. claims one property can be related to others for microcracked materials. Therefore, can different degraded material/damage states be accounted for?
  - Correlation of electrical conductivity, thermal conductivity, thermal diffusivity, and elastic modulus for microcracked materials
    - 23rd Ann. Conf. On Comp., Adv. Cer., Mtls., and Struct.: A 1999
- Formation into a design tool

NDC Life Determination and Prediction Justification (Pull)

- Models today don't always predict failure (have to go in and modify model after failure)
- Models are not run on all conditions
  - Off nominal and exact usage profiles
- Changes in design, real-time changes by mechanics, and differences in part print and part fabricated dimensions
- Parts wear out when they should not
  - If use 0% safety margin, then metal parts will fail before or after prediction--i.e. after all these years, we still can't accurately predict when metals will fail.
- Don't understand environment the parts are exposed to
  - Transient, nominal (temperature, gas composition, and their gradients, thermal & mechanical interactions, etc.), off nominal

AND this is for Metals…we have to be kidding ourselves if we expect to predict the life of CMCs using the same philosophies used in attempting to predict life for metals.

Conventional Life Prediction Success



Physics based life prediction is a stake in the sand.

*Notional numbers

Life Modeling Assumptions

- Conventional Physics Based (Reactive--stake in sand)
  - Properties of coupons correlate to components
  - Know environment component is exposed to
  - Part matches print
  - No gross changes in shape with time
- Nondestructive Life Determination and Prediction (Responsive--able to change to with time and adjust to operational nuances and true exposure conditions)
  - Detect, discern, and account for all damage modes of material

Physics based life prediction is base upon:
assumption upon assumption, and assumption upon assumption--thus large safety factors required.

Summary

- Idea put forth for NDC generated Algorithm-N curve to replace a S-N curve
- A scenario for NDC life determination has been proposed
- Challenges are many for NDC Life Determination and Prediction, but could yield a grand payoff
- Justification for NDC Life Determination and Prediction documented