Hot Section Silicon Nitride Materials Development for Advanced Microturbines and Other Gas Turbine Component Applications

NT154 Radial Microturbine Rotor

Saint-Gobain Ceramics & Plastics, Inc.

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Hot Section Silicon Nitride Materials Development

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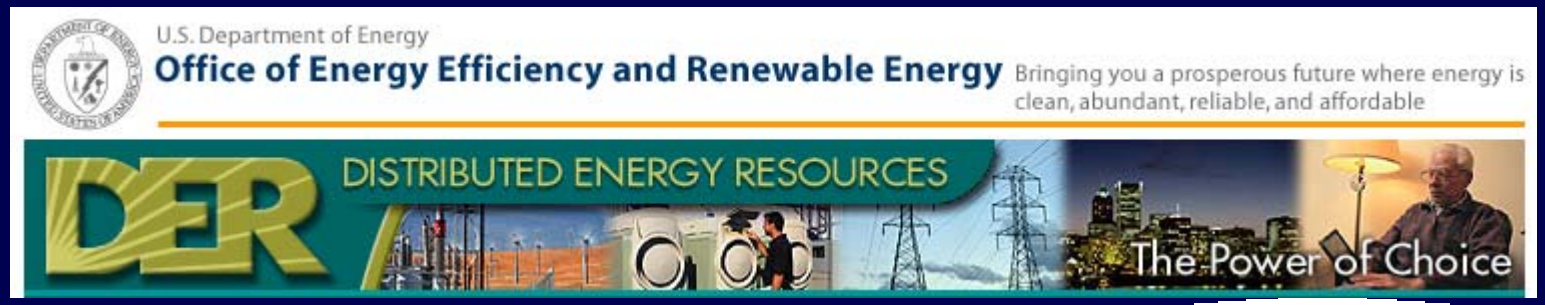

Purpose of the Work

Hot Section Si_3N_4 for Advanced Microturbine Program

- Phase I: Develop/optimize a cost-effective, reliable monolithic silicon nitride material for Hot Section Components in Advanced Microturbine Systems
- Phase II: Through surface engineering, demonstrate sufficient environmental stability for operation w/o EBC -- Or compatible with EBC

Overall Goals

- Contribute to AMTS Objectives of efficiency (40%), fuel flexibility, emissions (< 7 ppm NOx), durability (11,000 hr), operating cost ($500/kW)
- Expand utility of HT silicon nitride component for other power generation, aerospace and military applications

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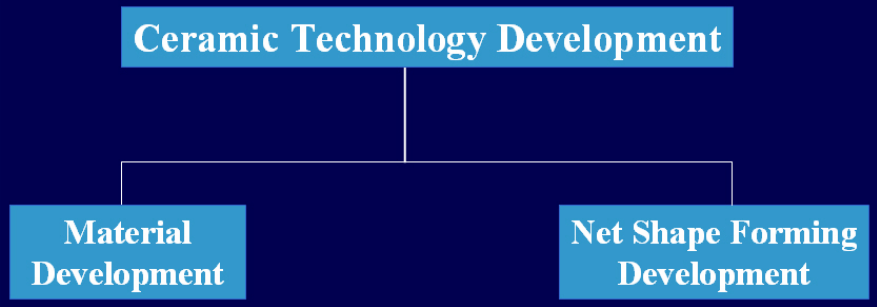
Outline



Background – Ceramics for Gas Turbines

Approaches

> Materials and Process Development

Materials Development Results

Process Development Results

Recession Control -- Next Steps, Phase II

Summary and Conclusions

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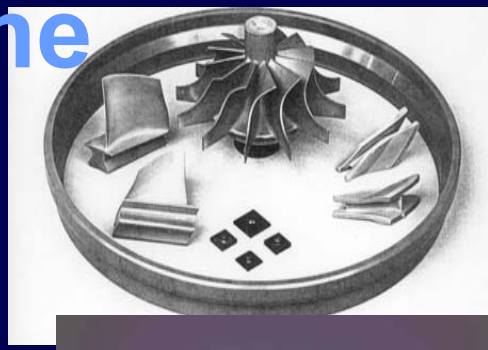
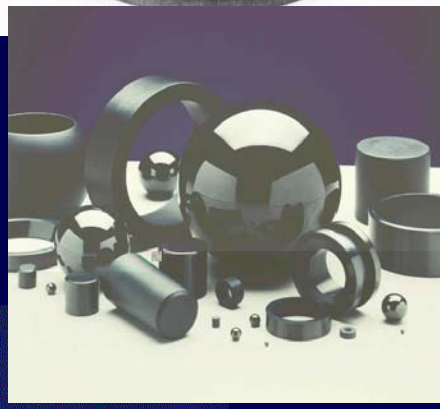
History - Ceramic Gas Turbine



DoD Ceramics for High Performance Applications – Bearings and Engines



DOE Automotive Gas Turbine Programs (80's-90's)

DOE ORNL Ceramic Technology (80's-90's)

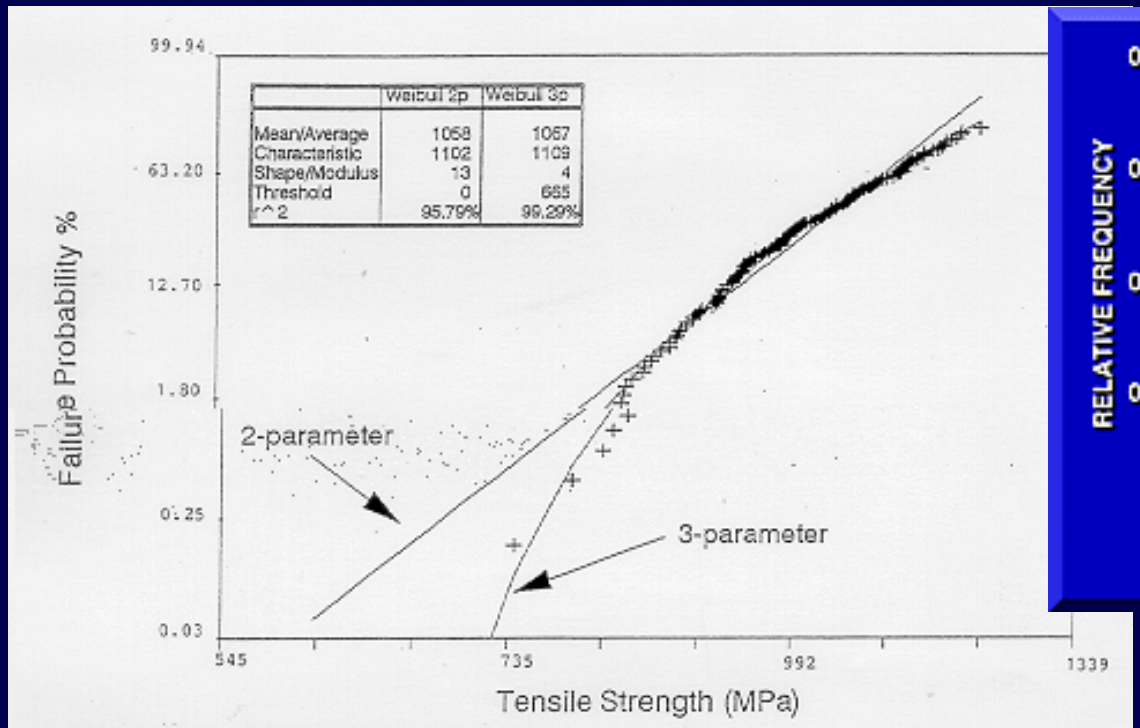
> RELIABILITY
- Life Prediction
- Norton Improved Processing

> COST-EFFECTIVENESS
- Valves, Unit Operations, Machining

Technology advances and spin-off

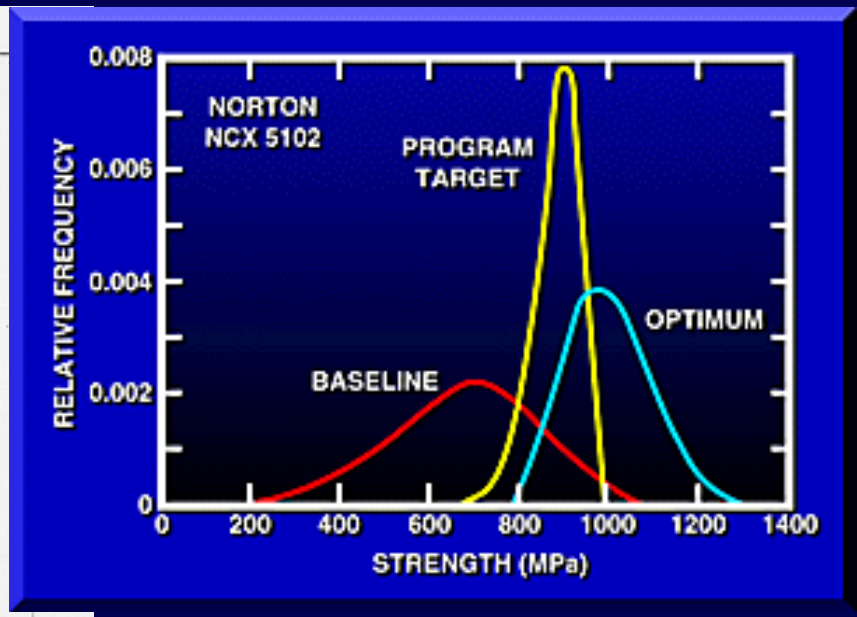
Strength Prediction

NCX-5102 Si_3N_4 Exhibits 3-parameter Weibull distribution for Intrinsic Flaws



	Weibull 2p	Weibull 3p
Mean/Average	1058	1067
Characteristic	1102	1109
Shape/Modulus	13	4
Threshold	0	665
r^2	95.79%	99.29%

Figure III: NCX-5102 Cumulative Probability of Failure for Intrinsic Tensile Strength Data from Competing Risk Analysis.



"Ceramic Technology for Advanced Heat Engines", D. Ray Johnson, ORNL, and Robert Schulz, U.S. DOE c.1995

Pujari, et al. (Norton Company), "Development of Improved Processing and Evaluation Methods for High Reliability Structural Ceramics for the Advanced Heat Engine Applications, Phase I", August 1993, p. ix.

Material and Process Approach

New ceramic materials must be compatible with a reliable, cost-effective forming process. Requires parallel path approach

Ceramic Technology Development

Material Development

- Re-establish NT154
- Improve NT154
- Recession Control
- Alternate Composition

Net Shape Forming Development

- Binder Development
- Green CNC Machining
- Casting / Molding

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Material Selection

High Temperature Advanced Monolithic Ceramics

Silicon Nitride

> NT154

> NT164

Silicon Carbide

> Hexoloy SA

Properties	Hexoloy SA	NT154
Description	Sintered Alpha SiC	HIPed Si_3N_4-4% Y_2O_3
Young's Modulus (GPa)	410	310
Hardness - Knoll (Kg/MM.)	2800	1620
RT Flexural Strength (MPa)	459	965
HT Flexural Strength (MPa)	450 @ 1200◦C 432 @ 1400◦C 404 @ 1500◦C	580 @ 1370◦C
Fracture Toughness* ($MPa \cdot m^{1/2}$) (Indentation Strength Method)	4.6	6.4
Thermal Conductivity (W/m-K) R.T. 1000ºC	 125 49 @ 600◦C	 38 @ 100◦C
Thermal Expansion (10^6/C)	4.02	3.9
Apparent Porosity %	2	0
Density (g/cm^3)	3.15	3.23
Electric Resistivity (Ω-cm)	10^6	-
Max Use Temp. ºC	~1650	~1370
Specific Heat (J/Kg-K)	670	

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Outline

Background – Ceramics for Gas Turbines

Approaches

> Materials and Process Development

Materials Development Results

Process Development Results

Recession Control -- Next Steps, Phase II

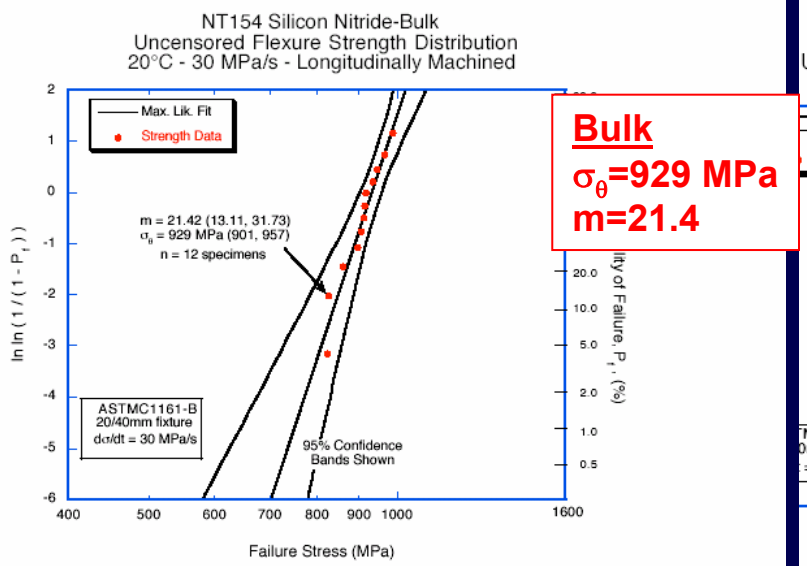
Summary and Conclusions

Room Temperature Fast Fracture

Delivery 1 Results

Testing at ORNL
by H.T. Lin

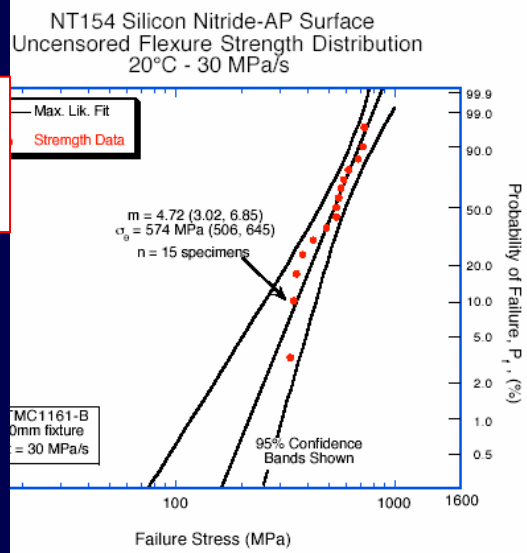
Results Obtained Consistent with the Reported Data for NT154-11C, but with a Higher Weibull Modulus



Bulk
σ_θ=929 MPa
m=21.4

NT154-11C: σ_{mean}: 948 MPa, m=8.6

h Obtained for Bulk Material **Strengt**



AP
σ_θ=574 MPa
m=4.7

NT154 also exhibited a low Weibull modulus (m =4.7)

The as-processed

➢ **Identified need to improve AP properties**

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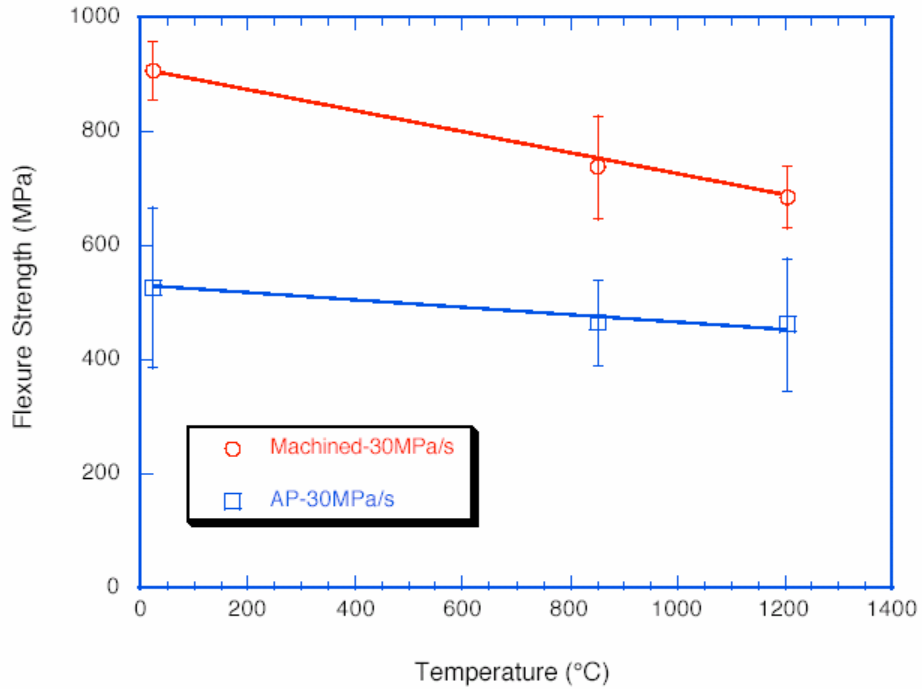
High Temperature Strength

NT154 Task I, Machined and AP Surfaces

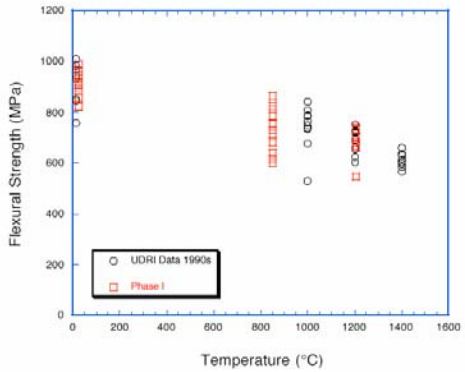
Testing at ORNL
by H.T. Lin

The NT154-11 w/ As-Processed Surface Exhibits Less Temperature-Dependence of Strength Than the Bulk



Good Match with historical data from ORNL and UDRI

The Mechanical Performance of NT154 Phase I Materials is Consistent to Those Manufactured in 1990s



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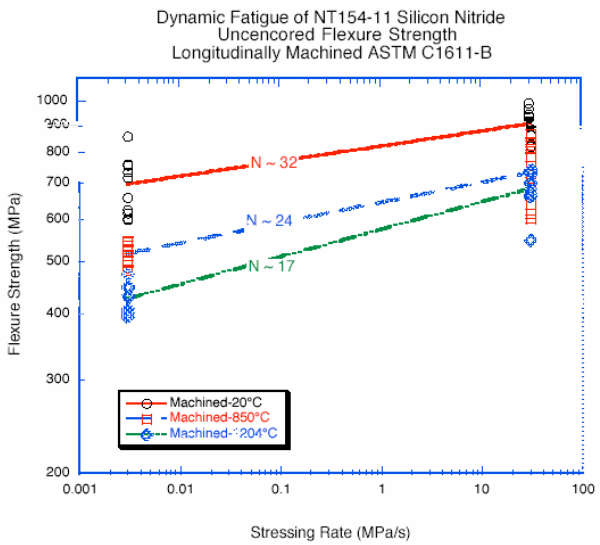
Dynamic Fatigue, Machined (Bulk) vs As Processed Surface

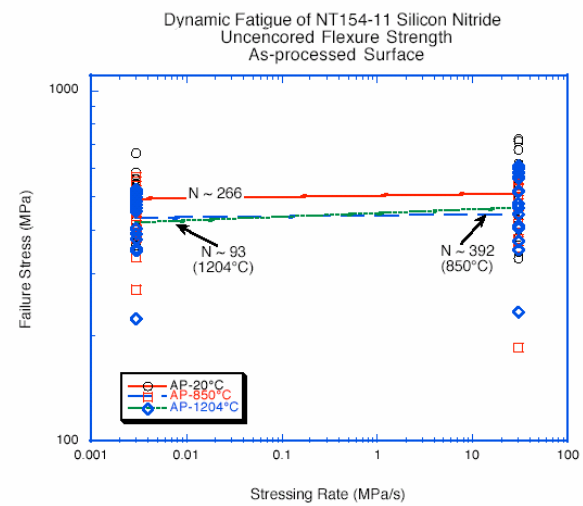
Testing at ORNL
by H.T. Lin

NT154 Task I

The NT154 Task I Materials Exhibited Low Dynamic Fatigue Exponents Between 20 and 1204°C



However, the NT154-11 with As-processed Surface Exhibited High Dynamic Fatigue Exponents up to 1204°C



- Fatigue exponents similar to historical data

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As-Processed Surface

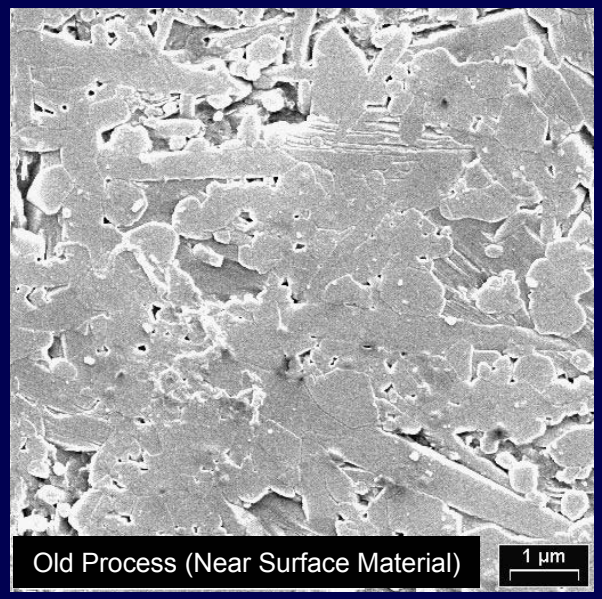
Proprietary New HIP Process

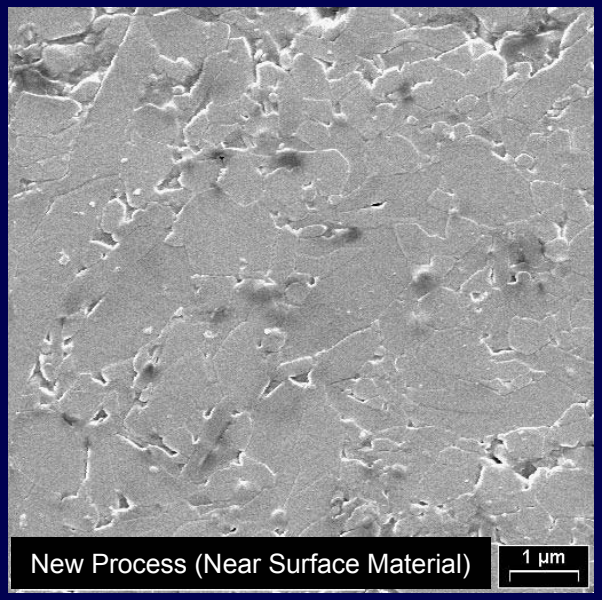
Looking to reduce the Si3N4 interaction with the HIP glass

- Influence on the near surface material

Initial experiments done in a laboratory scale HIP

Etched microstructure of the near surface material





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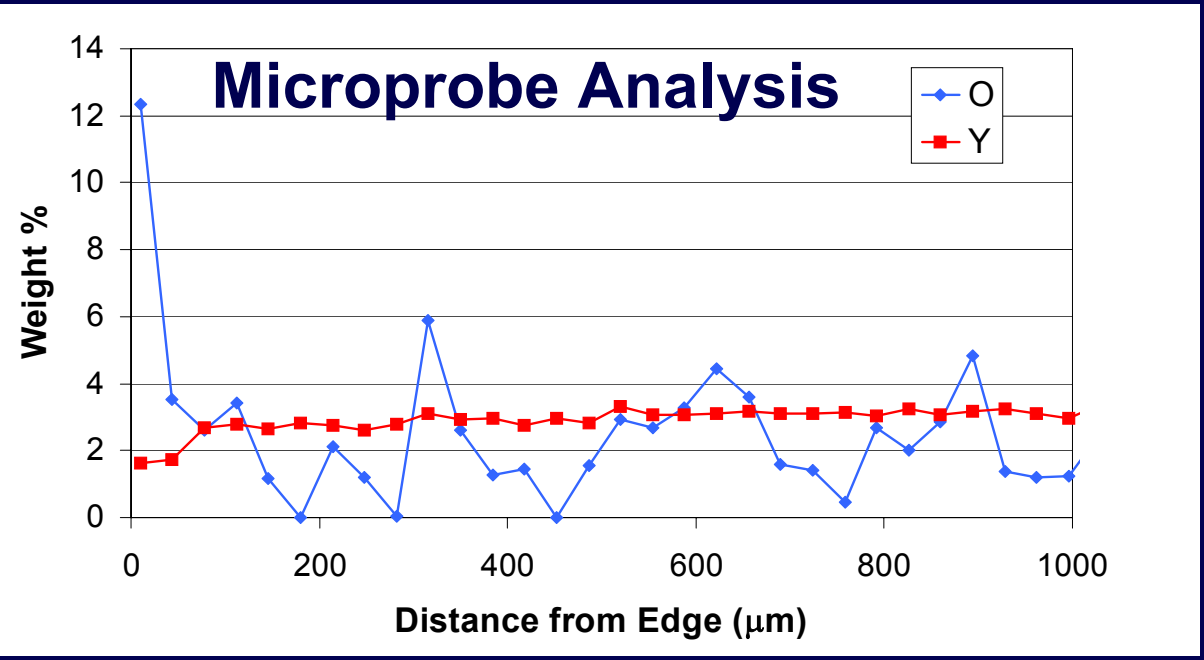
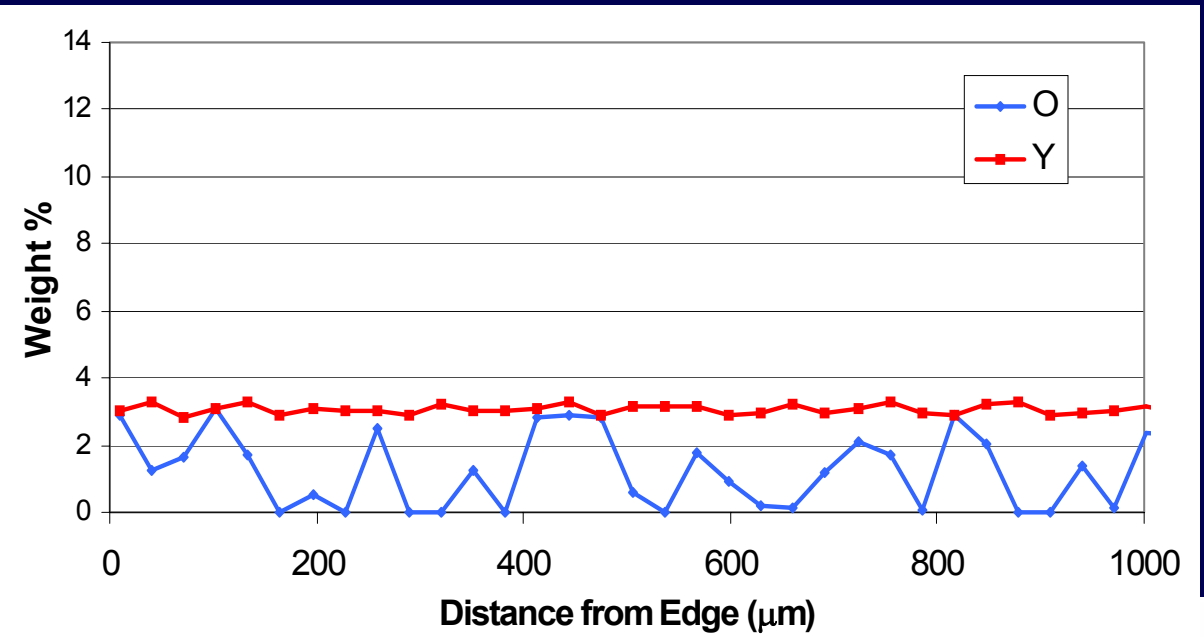
As-Processed Surface Improvement



Old Process



Proprietary New HIP Process

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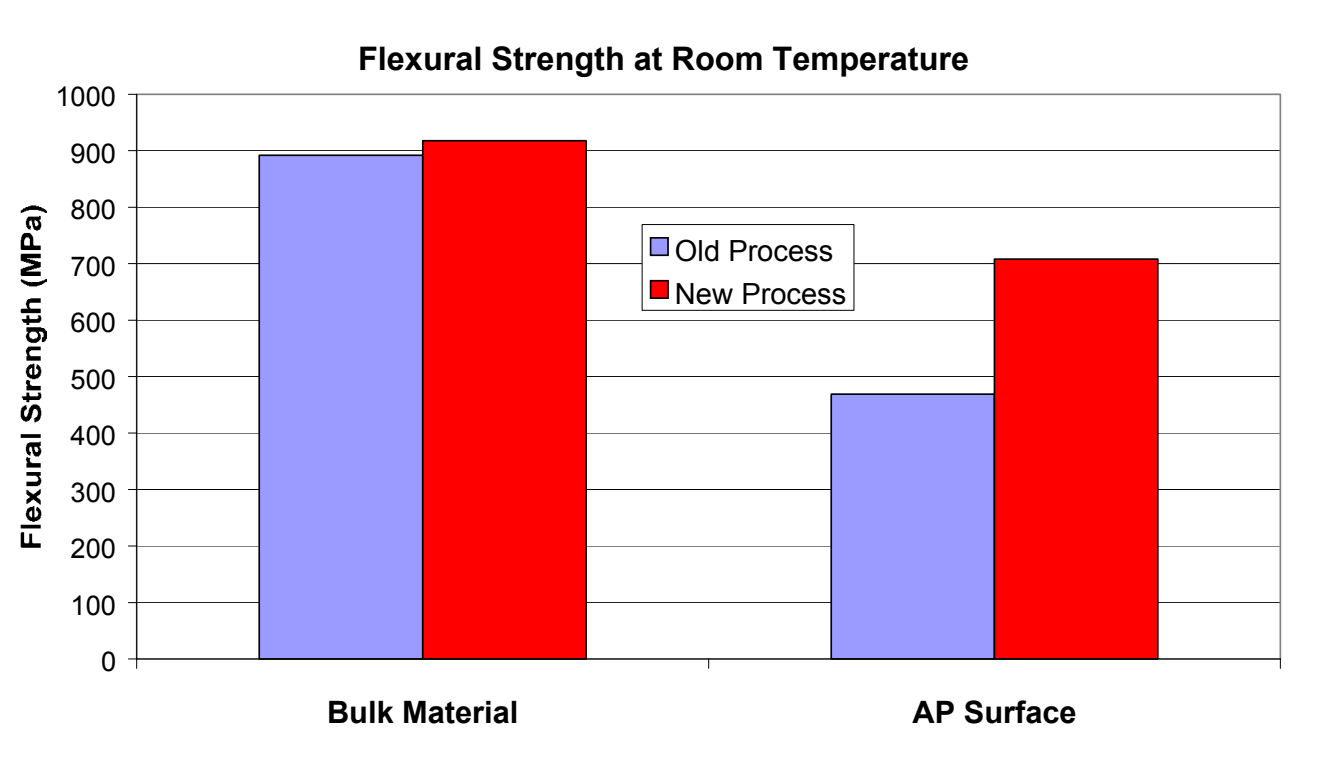
As-Processed Surface

Proprietary New HIP Process

Significant improvement in AP strength

- Important for net-shape turbine components



➢50% improvement in AP strength!

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> Materials and Process Development

Materials Development Results

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Process Development Results

Ceramic Microturbine Technology

Material Development

Net Shape Forming Development

- **Green CNC Machining**

- **Casting / Molding**

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Typical Ceramic Processing

	Process Examples
Powder Processing	Milling, Blending Slurry Prep, Spray Drying, Freeze Drying Freeze Granulation
↓ Forming	Dry Forming, Casting, Solid Casting/IM/TC, Layer Processing/RP
↓ Green Machining	CNC, single point tool
↓ Firing	Pressureless Sintering, GPS, HIP, HP
↓ Machining	Diamond Grinding, Lapping, Polishing
↓ Inspection	↑ In-process control

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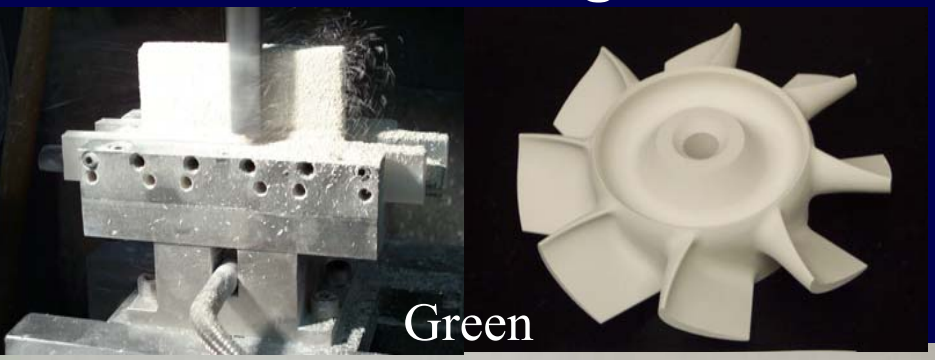
Net Shape Forming

Green Machining



- Developed green-machining process
- Design of Experiments to optimize cutting tools and machining parameters
- Completed demonstration axial rotors
- Green dimensions within 0.003" of nominal
- Dense surface roughness
  - Hub: 35-40 μin (0.9-1 μm)
  - Blades: 55-75 μin (1.4 – 1.9 μm)
- Uniform/isotropic shrinkage
- High yield
- Flexible prototyping process

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Net Shape Forming: Microturbine Rotor

Green Machining

- Ingersoll-Rand design
- Machining completed on four prototypes

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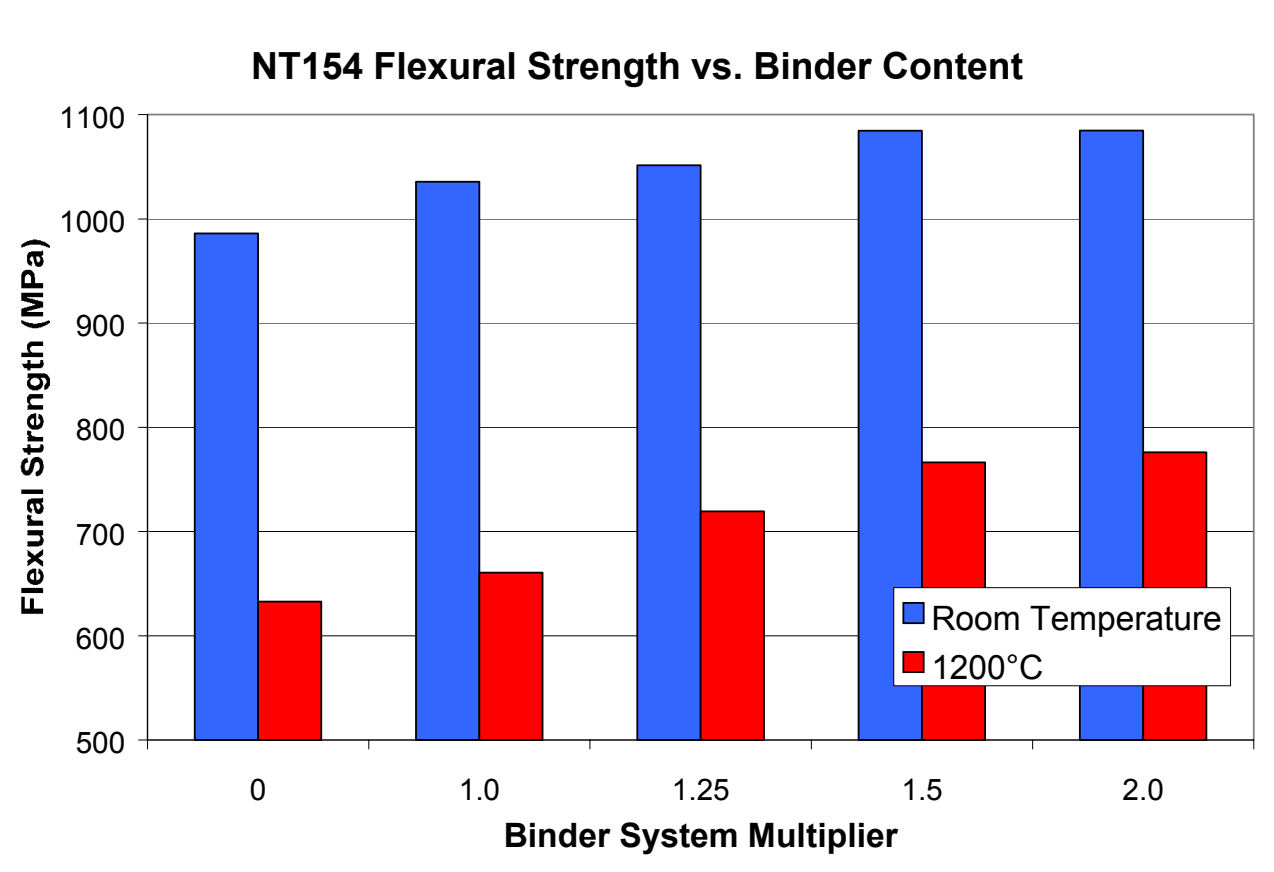
High Temperature Strength

Influence of Binder Level on Properties

Mechanical Properties (Bulk Material)



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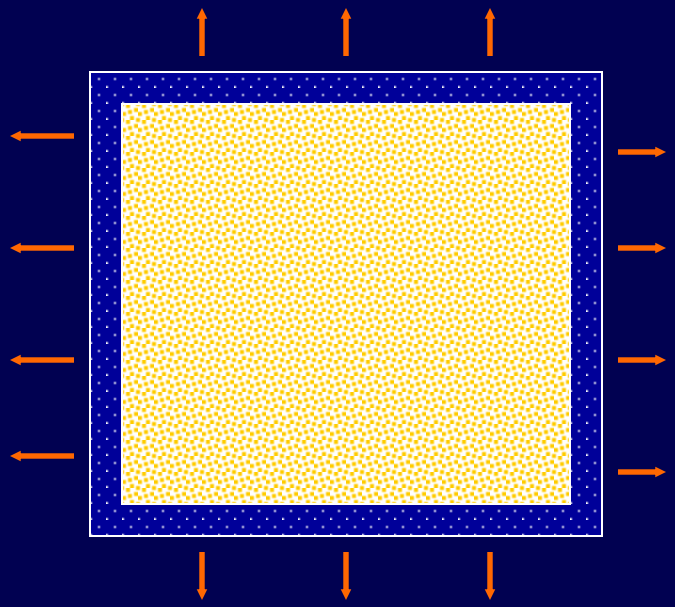
Net Shape Forming

Direct Starch Casting

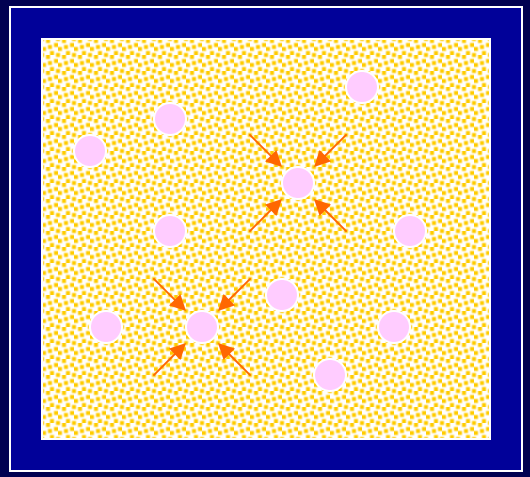
WATER MIGRATION

STARCH PARTICLE



POROUS MOLD

ROOM TEMPERATURE



NON POROUS MOLD

T= 60°C

SLIP CASTING (DRAINED)

→ DRYING SHRINKAGE

DIRECT STARCH CASTING (UNDRAINED)

→ NO DRYING SHRINKAGE

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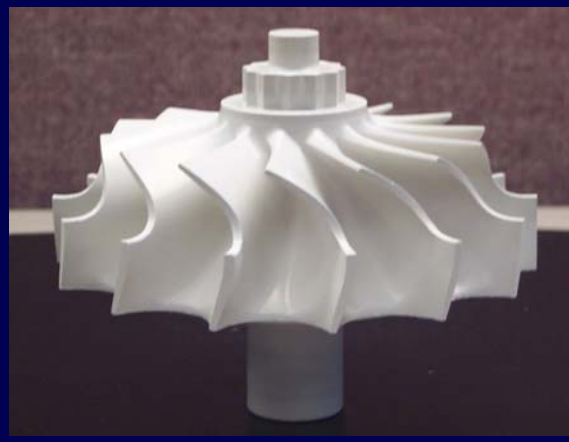
Microturbine Materials Plan For FY2004

Continue Material and Forming Advancements

- Reproduce improved AP properties in silicon nitride
- Continue to evaluate green-machining and direct casting approaches



NT154 Radial Microturbine Rotor

Phase II - Novel Recession Control

- ORNL Recession Testing
- Initial feasibility of an innovative protective layer
- "HEEPS" *in situ* Protective Surface vs EBC Approaches
- Collaboration with ORNL Pack Cementation Technique

Prototype Development in Support of OEMs

- Mechanical testing of a component at ORNL
- Plans to work with Microturbine Mfrs
- Defense Contractor Applications
- Cost Analysis

Summary and Conclusions

- **NT154 HT SN has been re-established**
- **Dual approach: Material and process development**
- **Improved AP strength through new HIP process**
  - Need to reproduce results in production HIP
- **Prototyping of rotors through green machining**
  - Improvements in high temperature strength via binder mod
- **Improvements in starch casting - Needs more work**
- **Novel Recession Control Development Underway**
- **Three invention disclosures filed**
- **Exploring new applications with Microturbine, Aerospace and Military OEM's**
  - Green Machining Approach