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

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Hot Section Materials Development For Advanced Microturbines Program

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> Dave Richerson, Dave Carruthers

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Purpose of the Work

Hot Section Si_3N_4 for Advanced Microturbine Program

- Under DOE/ORNL Program, Develop and improve a cost-effective, reliable monolithic silicon nitride material for Hot Section Components in DER Advanced Microturbine Systems
- Through surface engineering, demonstrate sufficient environmental stability for operation w/o EBC -- Or compatible with EBC

Overall Goals

- Contribute to AMTS Objectives of efficiency, fuel flexibility, durability, operating cost
- Expand utility of HT silicon nitride component for other power generation and military applications

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Outline

AMTS and Hot Section Material Goals

Historical - Silicon Nitride for GT Applications

Technical Activity -- Technical Progress and Plans

- > Material and Process Qualification
- > Materials
- > Process Development
- > Surface Engineering

Next Steps and Summary

DOE Advanced Microturbine Systems

25 kW to 500 kW (or to 1 MW)

Goals:

- Increase efficiency to > 40 %
- Enabling technology: ceramics and EBC
- Less than 7 ppm NOx
- Durability -- 11,000 hours bet major overhaul, 45,000 hour service life
- Cost of Power, $500/kW (now ~$1,000)
- Fuel Flexible
- DOE Funding $60 M FY 2000 - 2006

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DOE DER Microturbine System Development Programs

Original Prime Contractors

- Capstone
- GE
- Honeywell Power Systems
- Ingersoll Rand
- Solar Turbines (recuperator)
- United Technologies

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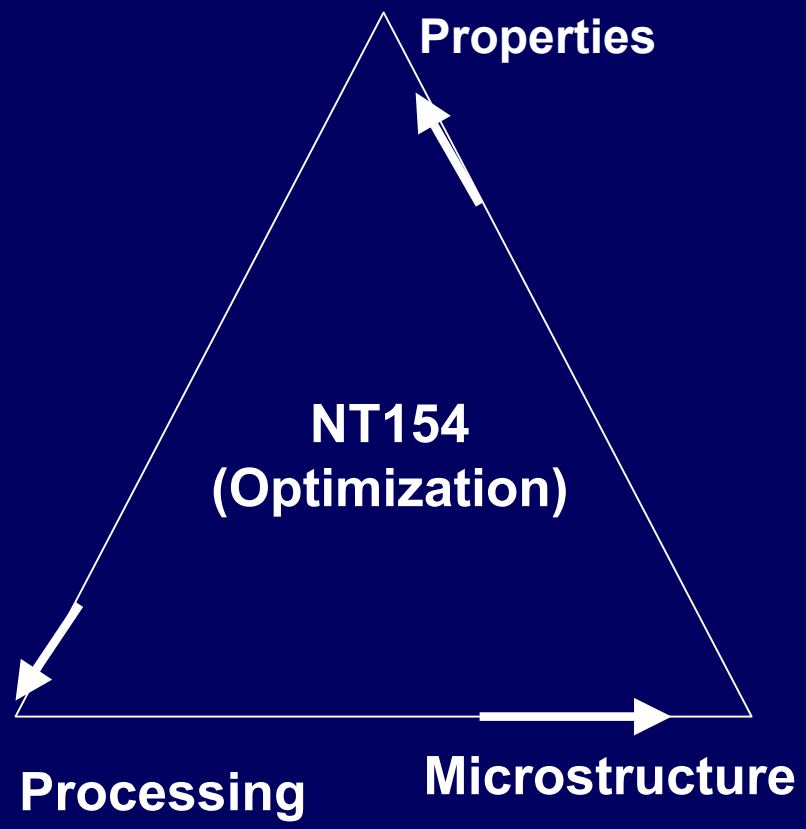
Materials Development Objective

Develop and optimize a high temperature ceramic material and process suitable for microturbine applications up to 1300°C.

Specific Properties

- **Fast Fracture**
  - RT – $\sigma \geq 950$ MPa
  - 1300°C $\sigma \geq 600$ MPa
- **Fracture Toughness ≥ 6.5 MPa$\sqrt{m}$**
- **Weibull Modulus ≥ 12**
- **High Temperature Creep Rate**
  $\approx 1.9 \times 10^{-8}$ @ 1250°C/130 MPa
- **Oxidation Resistance up to 1250°C**
- **Recession Resistance in humid environment up to 1250°C**



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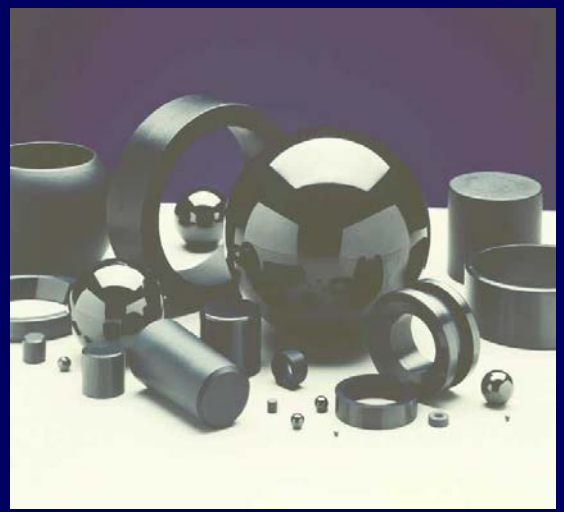
History - Ceramic Gas Turbine

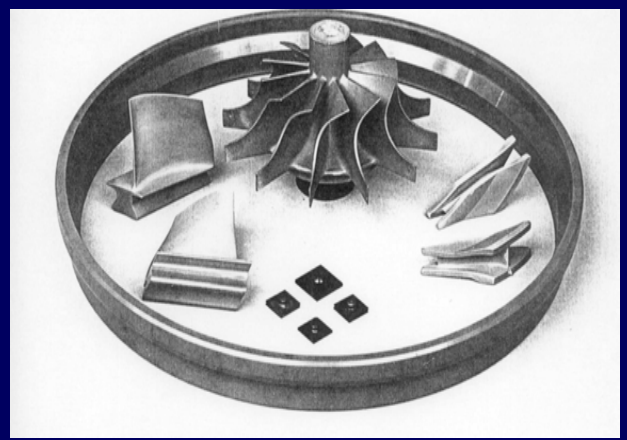
DoD Ceramics for High Performance Applications

- 70's & 80's: Army Conferences, NAVAIR Bearings
- NC-132 HPSN



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

- Allison, AlliedSignal Primes
- Norton/TRW NT154 SN, ASCC, Kyocera, Carborundum SiC



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History - Ceramic Gas Turbine

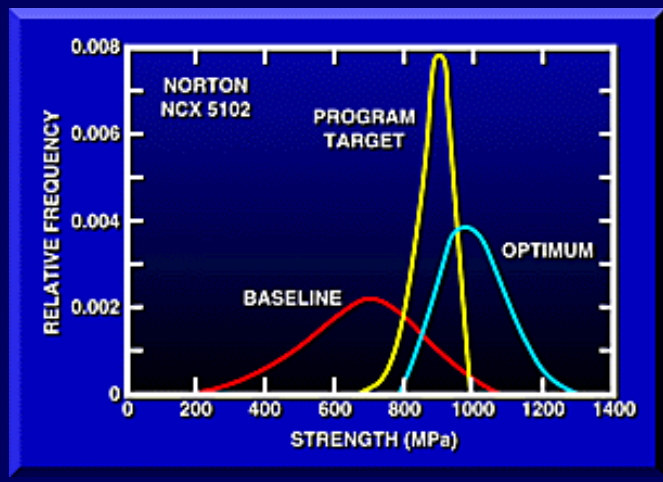
ORNL Ceramic Technology - DOE OTT (1983 Start)

> RELIABILITY

- Improved Processing - Norton/Saint-Gobain
- Life Prediction (Allison, AS, Norton/TRW)

> COST-EFFECTIVENESS

- Norton/DDC ACMT Valves, Innovative Grinding Wheel



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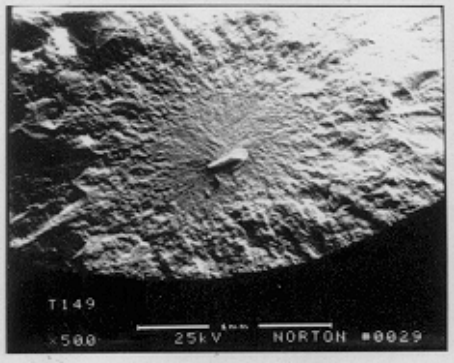
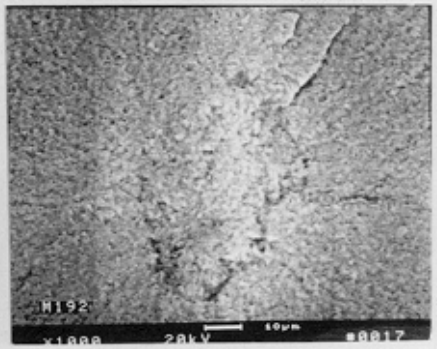
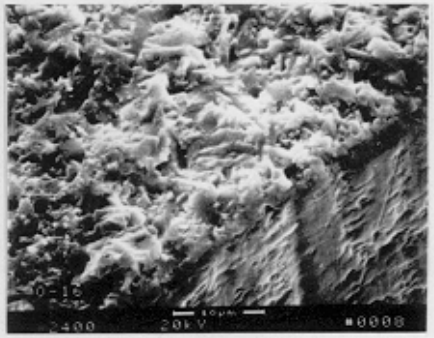
Chronology of Process Improvements for Si_3N_4



Injection molded tensile bar failed at 444 MPa due to 200μm metallic inclusion

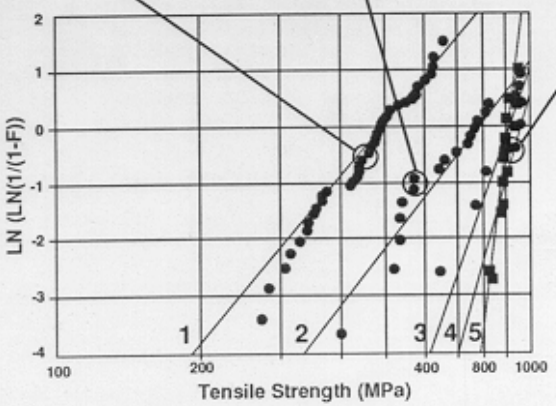


Fracture surface of pressure cast tensile bar which fractured at 570 MPa from 65μm agglomerate



Failure origin at surface of 884 MPa strength tensile bar centered about a 5μm wide machining groove from iteration 4

1. I.M. Baseline: m=4.2
2. P.C. Baseline: m=4.7
3. C-Series only: m=10.1
4. Iteration 3: m=13
5. Iteration 4: m=28



Tensile Strength data illustrating improvements from injection molding baseline iteration (Weibull modulus m=4.2, characteristic strength σ_0=492MPa) to pressure casting iteration 4 (m=28, σ_0=904MPa)

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Technical Activity -- Material Selection

High Temperature Advanced Ceramics, ATTAP

Silicon Carbide

> Hexoloy SA

Silicon Nitride

> NT154 w. CLP (NCX5102)

> NT164

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·m^{½}) (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/cm³)	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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Strength Prediction - Weibull 2p vs. 3p

NCX-5102 4%Y-Si_3N_4 Exhibits 3-parameter Weibull distribution

.25" Buttonhead Tensile rods

320 data points

With 3-paramenter

- > 1057 MPa mean
- > 685 MPa Threshold

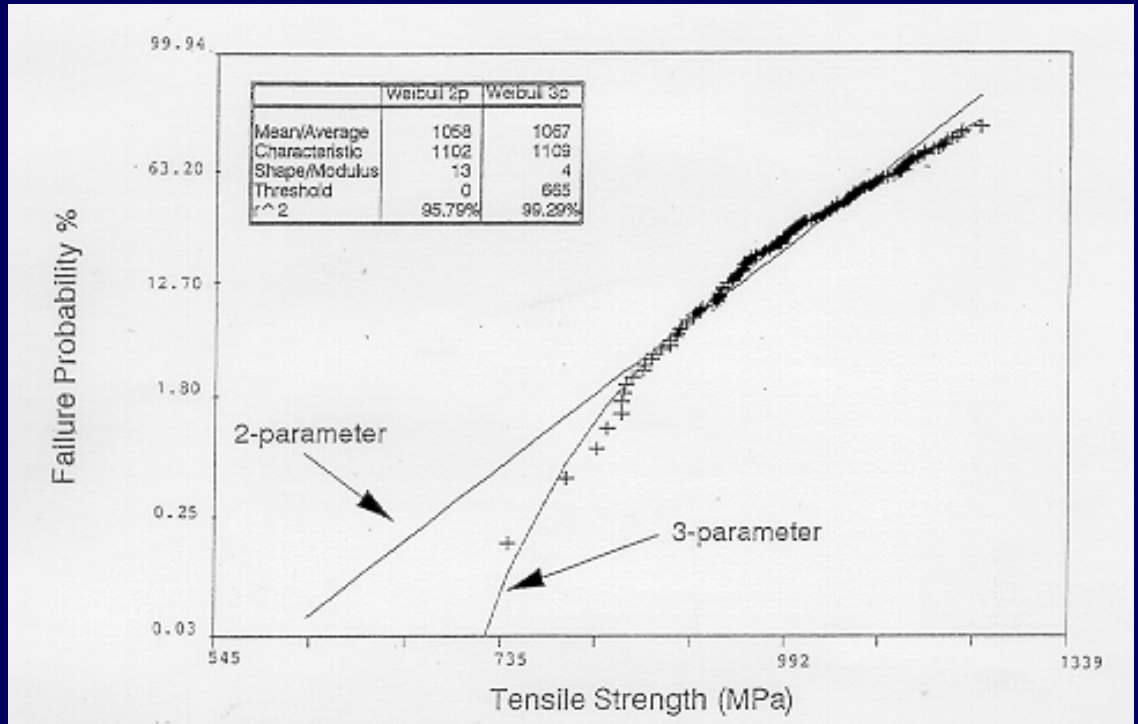

Figure III: NCX-5102 Cumulative Probability of Failure for Intrinsic Tensile Strength Data from Competing Risk Analysis.

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.

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Life Prediction - High Temperature

Load, Time, Temperature, and Environmental Effects

- **Creep**
  - Plastic deformation

NT154 Si_3N_4

Liu, Stevens, and Brinkman (ORNL), "Tensile Stress-Rupture Development", Ceramic Technology Project Bimonthly Technical Progress Report, October 30, 1993, p. 58.

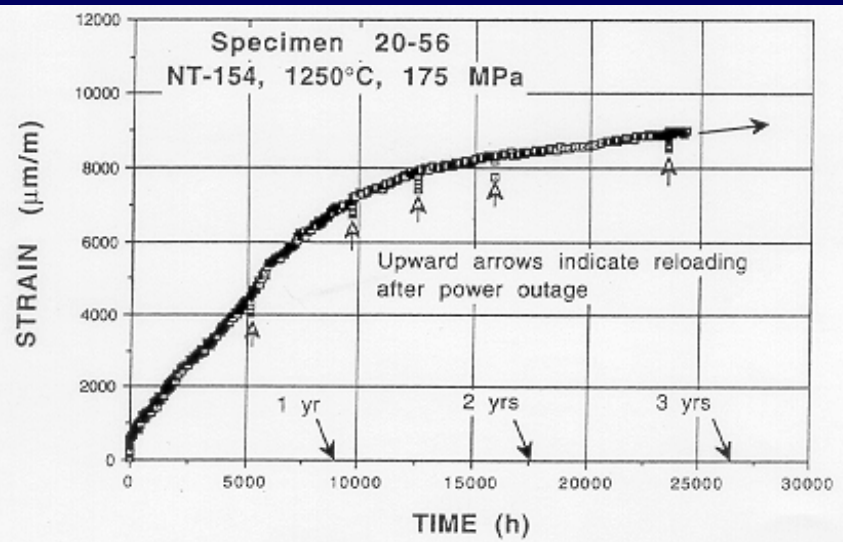

Fig. 3. Creep curve of NT-154 Si_3N_4 (specimen 20-56) tested at 1250°C and 175 MPa. No indication of imminent failure has been observed after nearly three years of testing.

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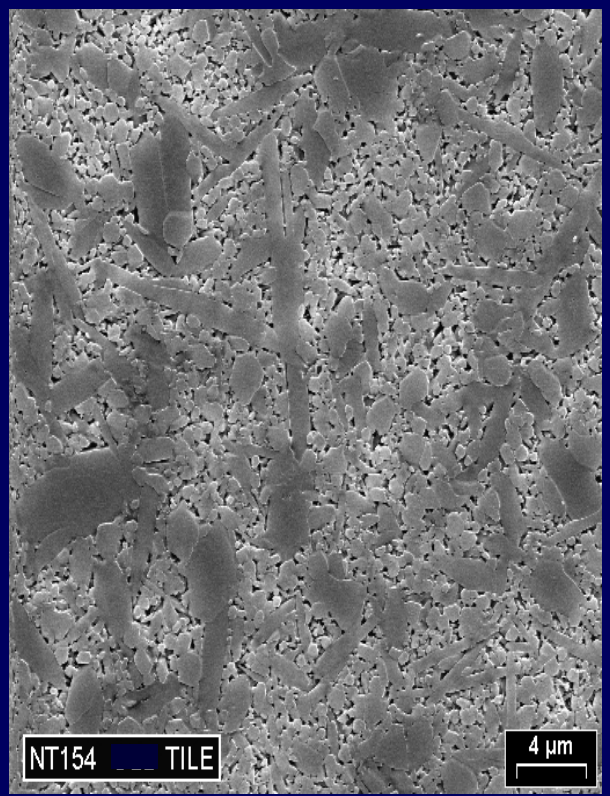
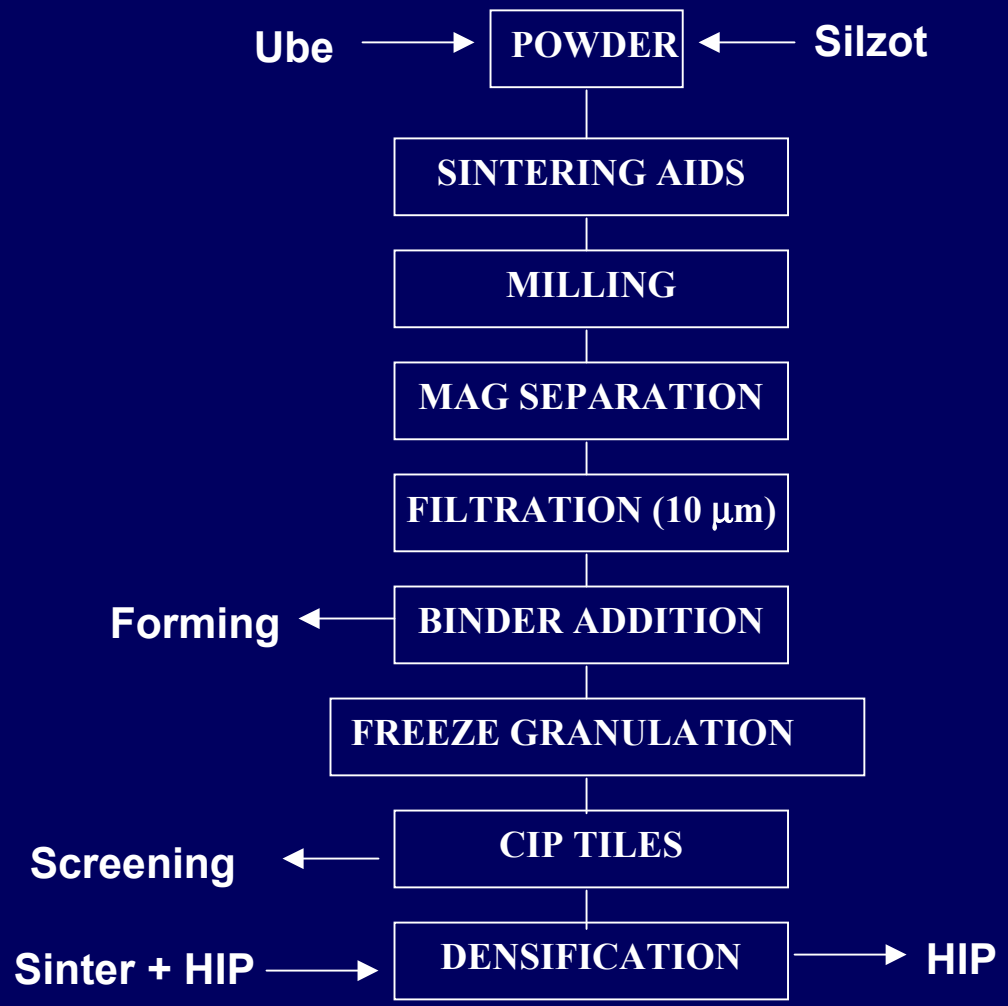
Material Screening/Selection

COMPOSITIONS

- NT154
- NT164
- β- SiAlON



CLOSED LOOP PROCESSING



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Material and Process Qualification

Viable Process

> Yield

> Scalability

Qualification of material properties must be consistent with cost-effective process

> Properties of large cross section vs. tile

> Surface properties, reaction layer, environmental resistance

> As-processed surface vs. machined surface

> Machining anisotropy

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Material and Process Approach

Ceramic Microturbine Technology

Material Development

- **Re-establish NT154/NT164**
- **β-SiAlON Development**

Net Shape Forming Development

- Two Initial Options
- **Green CNC Machining**
- **Direct Casting**

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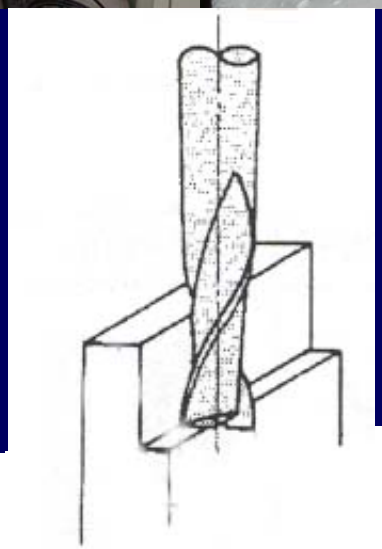
Green Machining Test Setup



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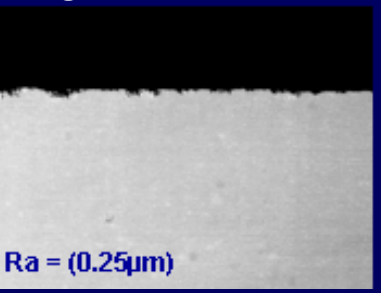
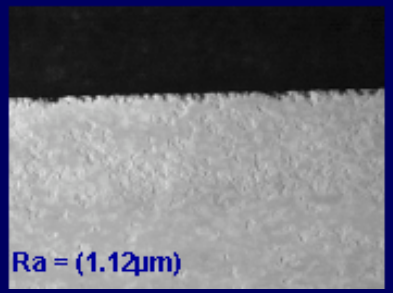
Machined Surface (NT154-6B)

New



Ra = (0.25μm)

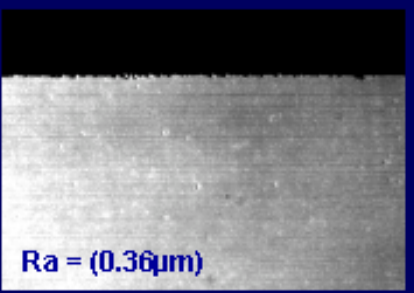
After 1.8m



Ra = (1.12μm)

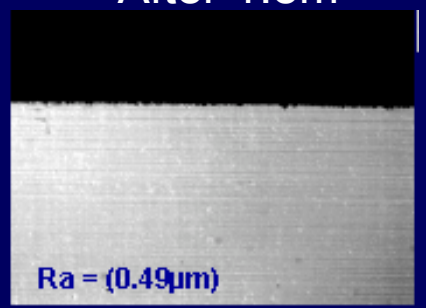
Carbide

New



Ra = (0.36μm)

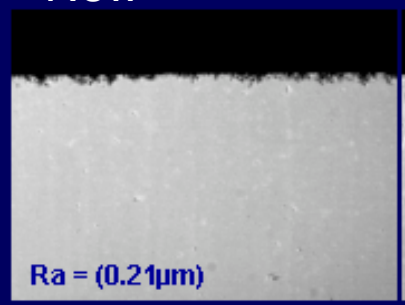
After 1.8m



Ra = (0.49μm)

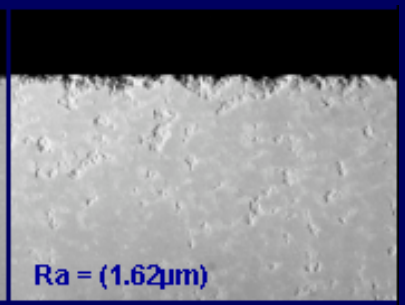
Diamond Coated

New



Ra = (0.21μm)

After 1.8m



Ra = (1.62μm)

TiN Coated

- **Green Machining Optimized**
- **CNC Machining Trial of Rotor**

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Complex Green Machining Trials

Dense Ra > than green

Preliminary trial

- > 0.7-0.9 μm Ra hub
- > 1.5-2.4 μm Ra blades

Surface finish can be controlled.

Uniform/isotropic shrinkage

High yield, low warpage

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Direct (Starch) Casting

- Net shape mold fabrication
  a) Pattern
  b) Net shape mold fabrication with RTV
- Slurry De-airing at 25 Hg. Of vacuum
- Casting
  a) Mold Filling by pouring
  b) Mold Filling under pressure
- Automated Mold Set Up

Direct Casting in RTV Mold

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Material Property Optimization

- **RT and HT Properties**
  - Beneficial Reaction Layer
  - Both Machined and AP Surface
  - FOD/DOD Protection
  - Qualification with ORNL
- **Environmental Effects**
  - Chemical Composition Optimization
  - Initial Feasibility of HIP Engineered Environmental Protective Surface (HEEPS)
  - ORNL Keiser Rig Testing
- **Formability**
- **Process Reproducibility / Reliability**
- **Cost Effectiveness**

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Environmental Effects

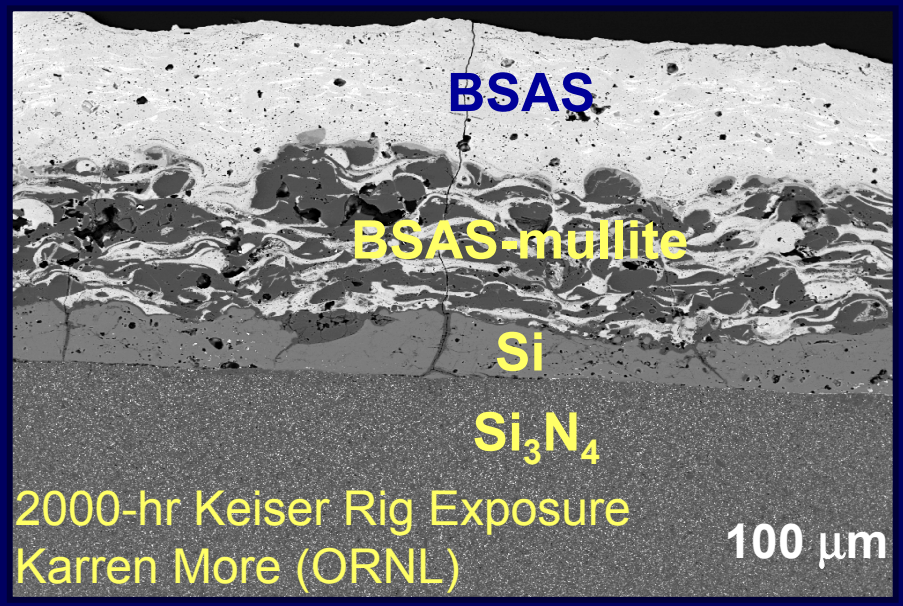
Recession Control Approaches

Composition Adjustment

Surface Engineering (HEEPS)

> Development of *in-situ* protective coating during the glass HIPing process step.

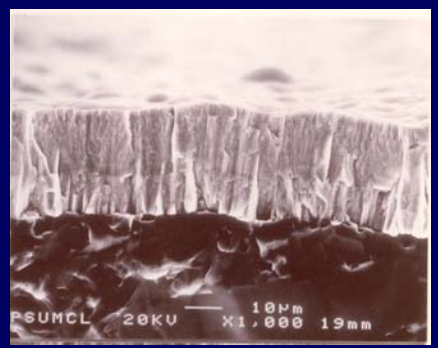
- Coat, then densify
- **Thermochemical Analysis Underway**



United Technologies Research Center

EBC

> Post-densification application of a protective layer



Dense Y_2O_3 on SiC by EB-PVD

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Program Status 2002

- **Closed Loop Powder Processing Established**
  - Achieved historical data strength
- **Net Shape Forming**
  - **Binder for CNC Green Machining Optimized**
  - **Starch based direct casting (DC) slurry developed**
  - **Surface finish optimization in progress**
- **Material Qualification**
  - UTRC NT154 Hubs
  - NT154 Gen A and B for ORNL
  - Preliminary Surface Engineering

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Summary and Conclusions

Si_3N_4 potential enabling material for high efficiency advanced microturbines

- > High perf. industrial, transportation and military applications
- > Ceramic suppliers, engine builders, national labs, and government

Saint-Gobain Program re-introducing NT154 family

- > Baseline properties achieved
- > Process development underway: Two Approaches
- > Qualify large X-section, as-processed and machined surfaces

Challenge of Environmental Stability in GT

- > Developing Recession Control Strategies
- > Novel in-situ surface modification approach
- > EBC development continuing

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