Generation of NT154 Si_3N_4 Mechanical Database for Advanced Microturbine Applications

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U. S. DEPARTMENT OF ENERGY

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Presentation Outline

- Background and Objective of Effort

- Experimental Procedures
  - Materials
  - Test conditions

- Results
  - Weibull strength distribution
  - Strength versus test temperature
  - Fatigue exponent

- Summary

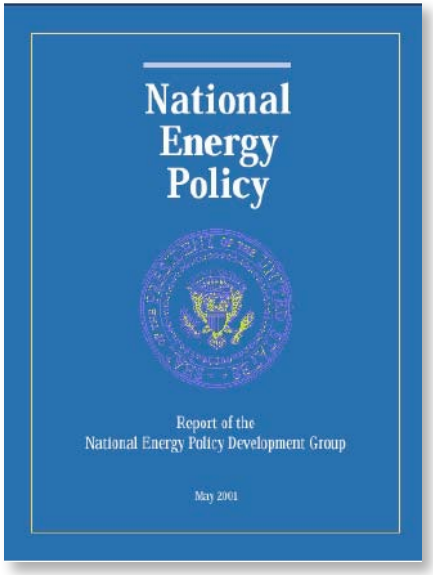
Distributed Energy Resources Provide a Secure New Energy Infrastructure for the U.S.

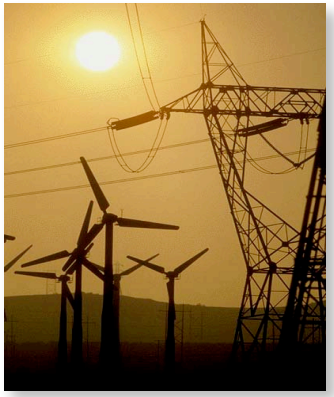
Vision 2020:

The United States will have the cleanest and most efficient and reliable energy systems in the world by maximizing the use of affordable distributed energy resources.

- Diversity of energy supplies
- "Fuel independent" technologies
- Flexible electric power grid
- Distributed on-site locations
- Advanced communications and controls
- Alternative transportation fuels

Clean ENERGY for the 21st Century





Office of Distributed Energy: Advanced Microturbine Program

Six year program (FY 2000 - 2006), $60+ million Govt. investment

Goals (by 22006):

- **High Efficiency** - Fuel-to-electricity conversion efficiency of at least 40%
- **Environmental Superiority** - NOx < 7 ppm (natural gas)
- **Durable** - 11,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours
- **Economical** - System costs < $500/kw, costs of electricity that are competitive with the alternatives (including grid) for market applications
- **Fuel Flexible** - Options for using multiple fuels including diesel, ethanol, landfill gas, bio-fuels

Advanced Microturbine Projects

FY00 – 5 Awards

- Ingersoll-Rand
- UTC
- GE
- Capstone
- Solar Turbines

Capstone

PowerWorks

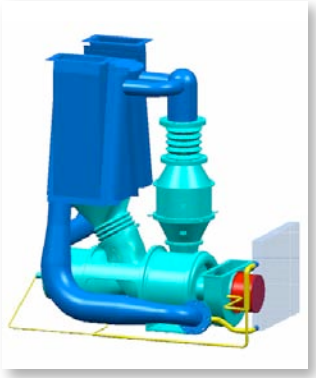
2000

- 17-30% Efficiency
- Double digit ppm NO_x

Average cost share for total program ~ 50%, staged over development – 30, 45, 60%

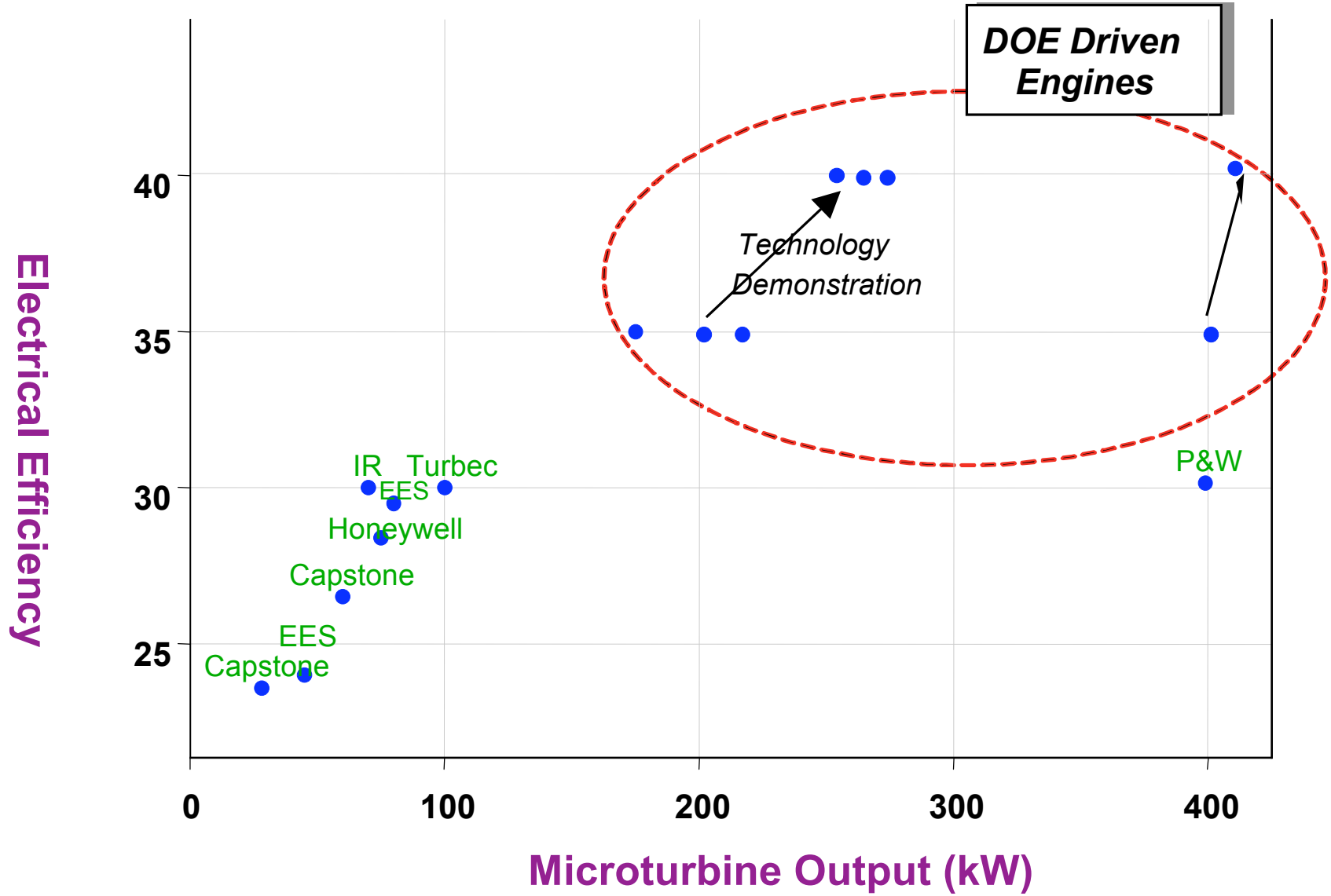
2006

- 40% Efficiency
- Single digit ppm NO_x

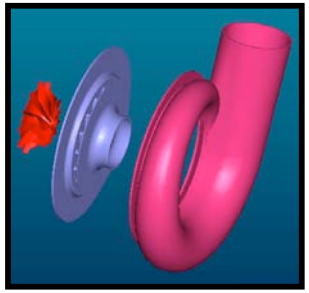


United Technologies Research Center

Anticipated Outcomes of Advanced Microturbine Program From DOE

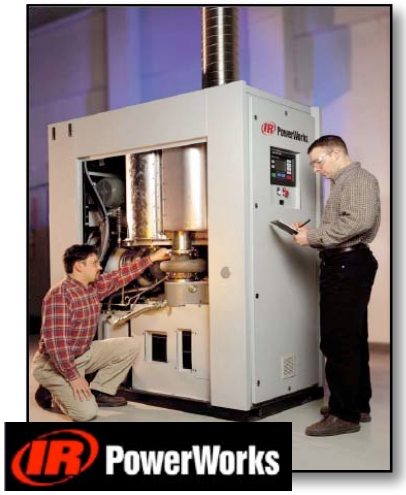


Advanced Ceramics are the Key Enabling Technology for Advanced Microturbine Systems

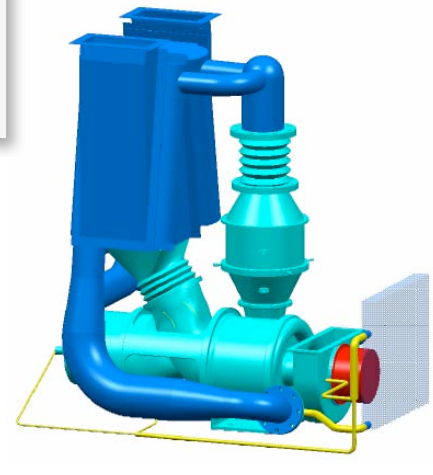


GE Global Research

Capstone



PowerWorks



United Technologies Research Center

Silicon nitride components have been designed and implemented for microturbine engines

Advanced Silicon Nitride Ceramics for Hot Section Components Project (FY 2002)

SAINT-GOBAIN
CERAMICS & PLASTICS

- Saint-Gobain was awarded by DOE in FY2003 to re-establish NT154 silicon nitride for hot section components applications in advanced microturbine system
- NT154 silicon nitride was considered candidate material for DOE OTT Ceramic Technology for Advanced Heat Engine Program and Heavy Vehicle Propulsion System Materials Program
- The high-temperature mechanical properties (fatigue, slow crack growth, and long-term creep studies) of NT154 silicon nitride have been extensively characterized throughout the program
- The mechanical properties of re-established NT154 have been evaluated by ORNL under Microturbine Materials Program

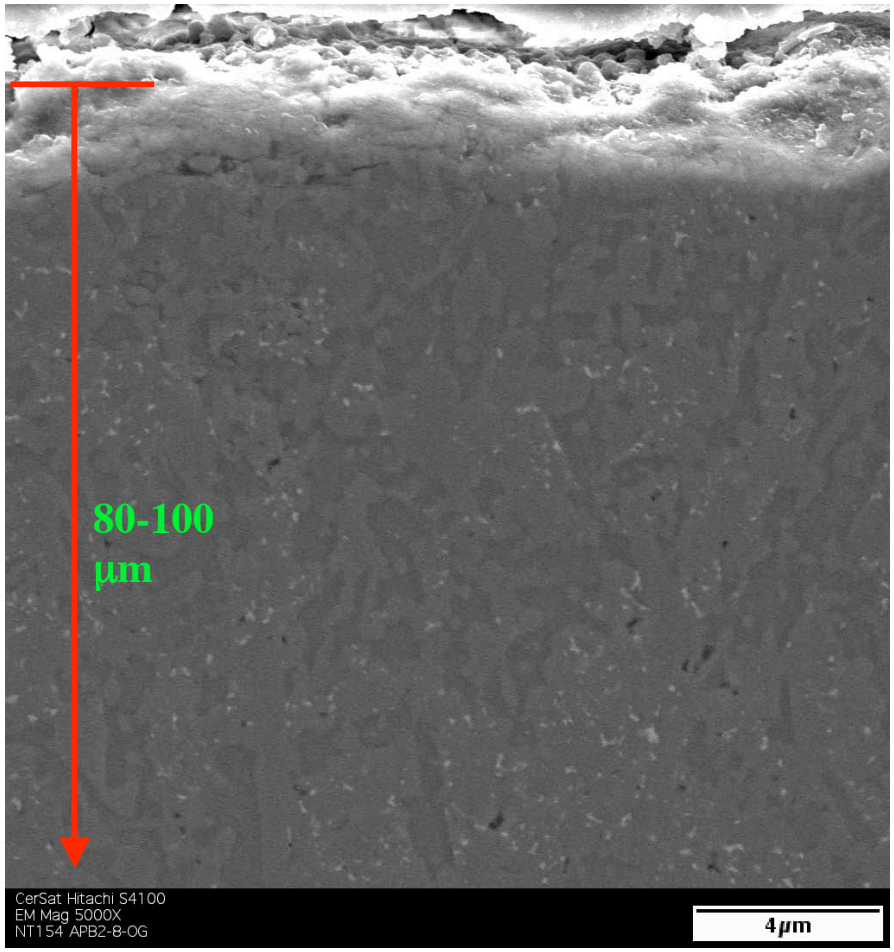
Objective

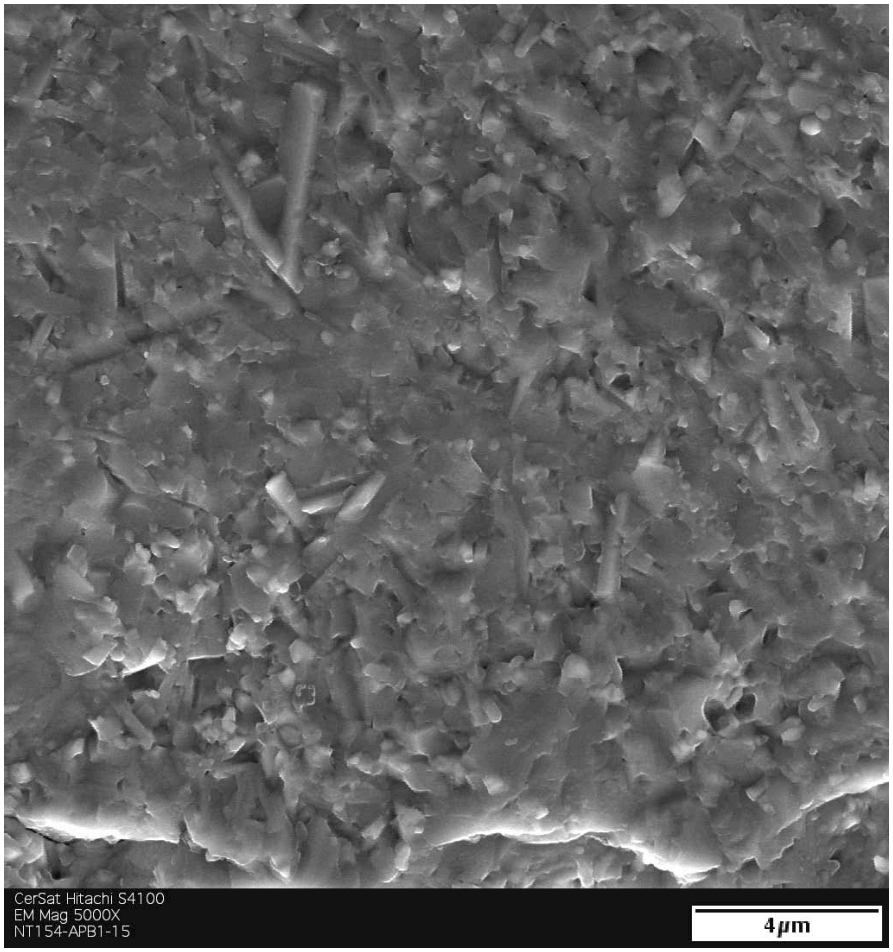
- ❑ Evaluate the mechanical properties consistency using those obtained in 1990s as the baseline
- ❑ Develop mechanical database for probabilistic component design and life prediction efforts of microturbine OEMs

Experimental Procedures

- NT154 silicon nitride (~ 15% α -85% β w/$Y_2Si_2O_7$) via glass encapsulation HIP process
  - NT154A (no organic processing additive)
  - NT154B (contains green machining binders
- ASTM MOR bend bars with 600 grits surface finish (ASTM C1161B-2002) and with as-sintered surface
- Dynamic fatigue studies (in air) (ASTM C1368 & C1465)
  - Temperature: 20, 1000, and 1204°C
  - Stressing rate: 30 MPa/s and 0.003 MPa/s
- Fractography and SEM analysis

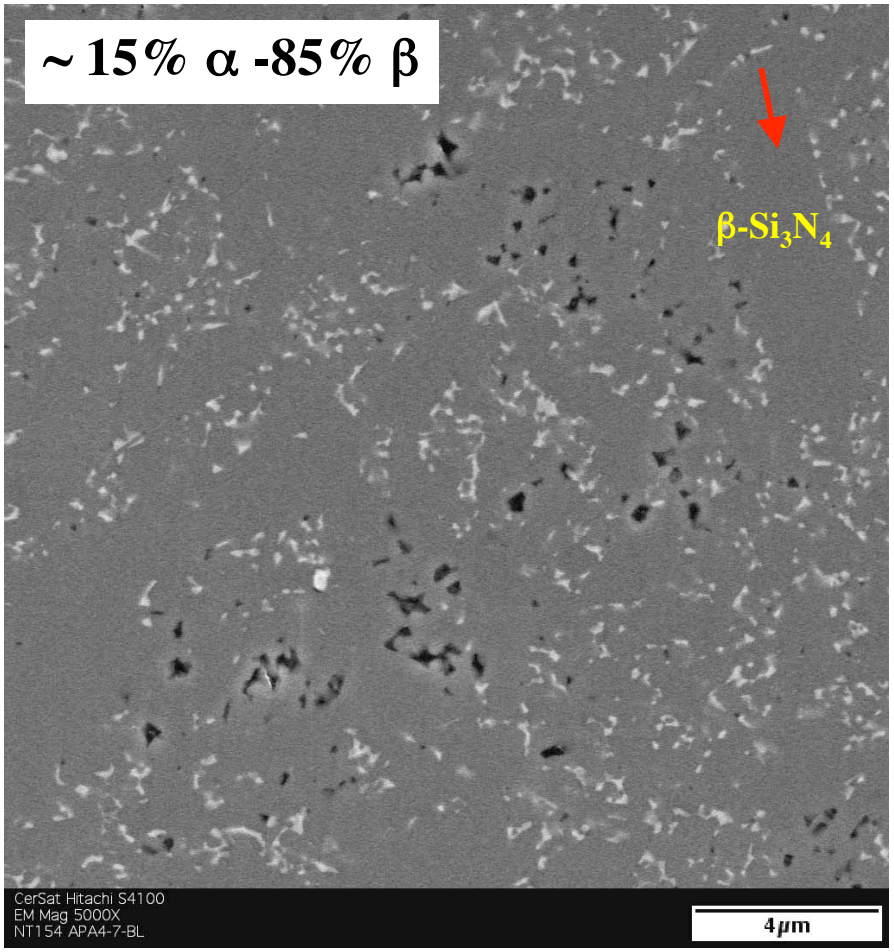
Representative SEM Micrographs of NT154 Silicon Nitride with As-Processed Surface Region

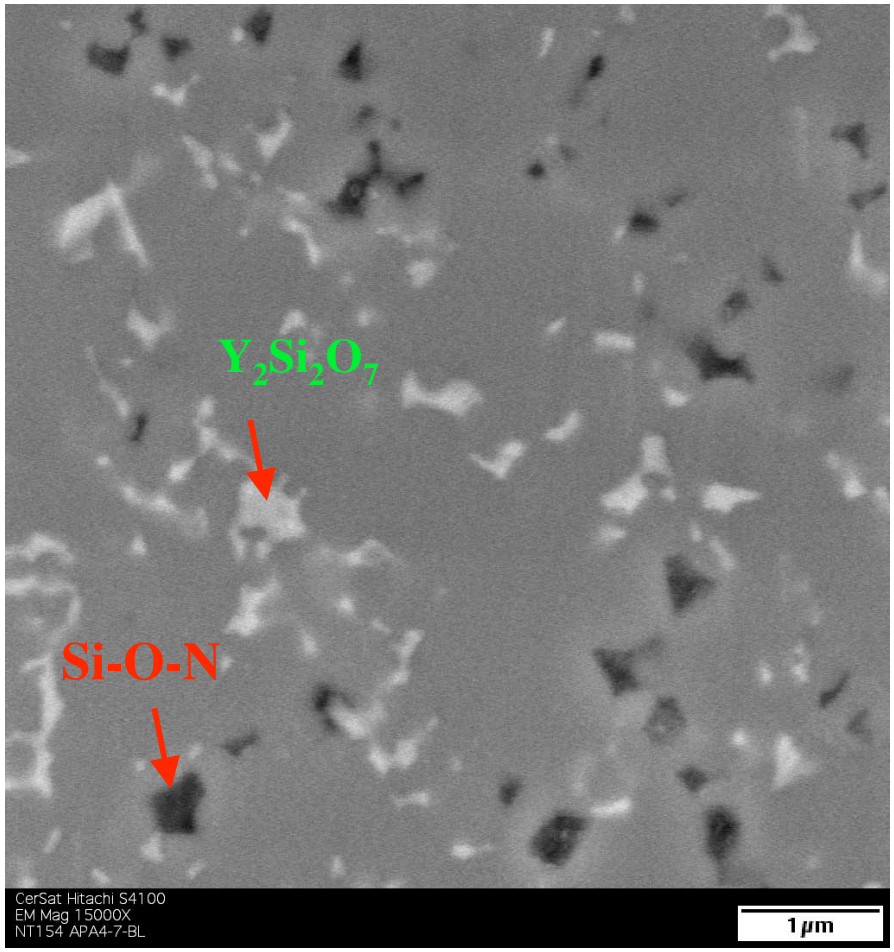




The “brittle” surface reaction layer (oxynitride crystalline phase) would probably degrade the mechanical performance

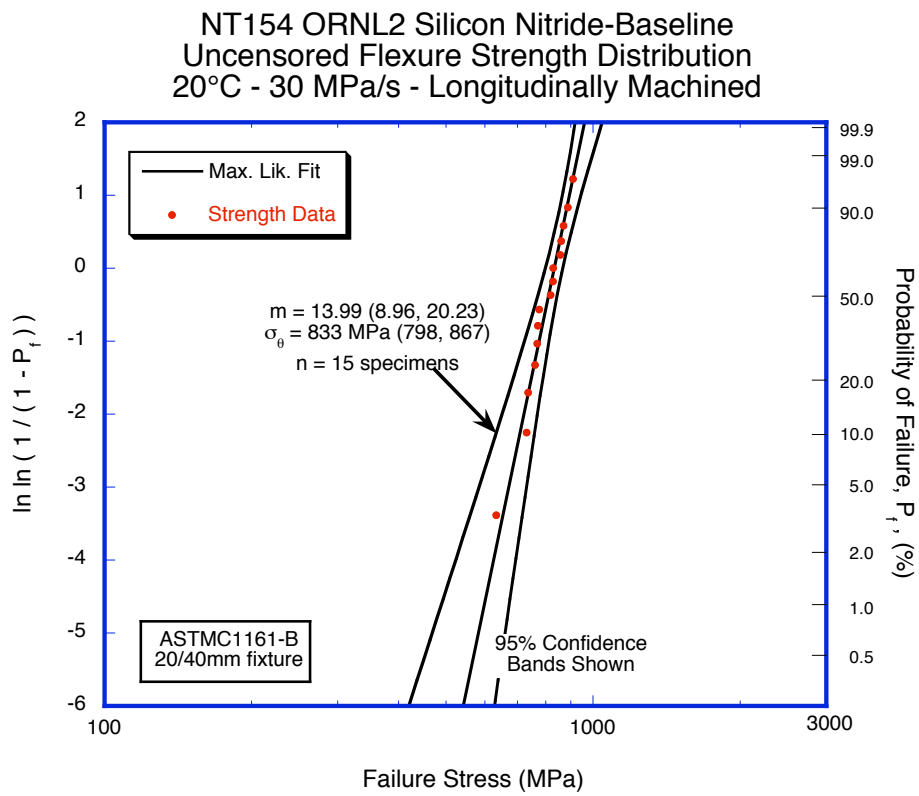
Representative SEM Micrographs of NT154 Bulk Region

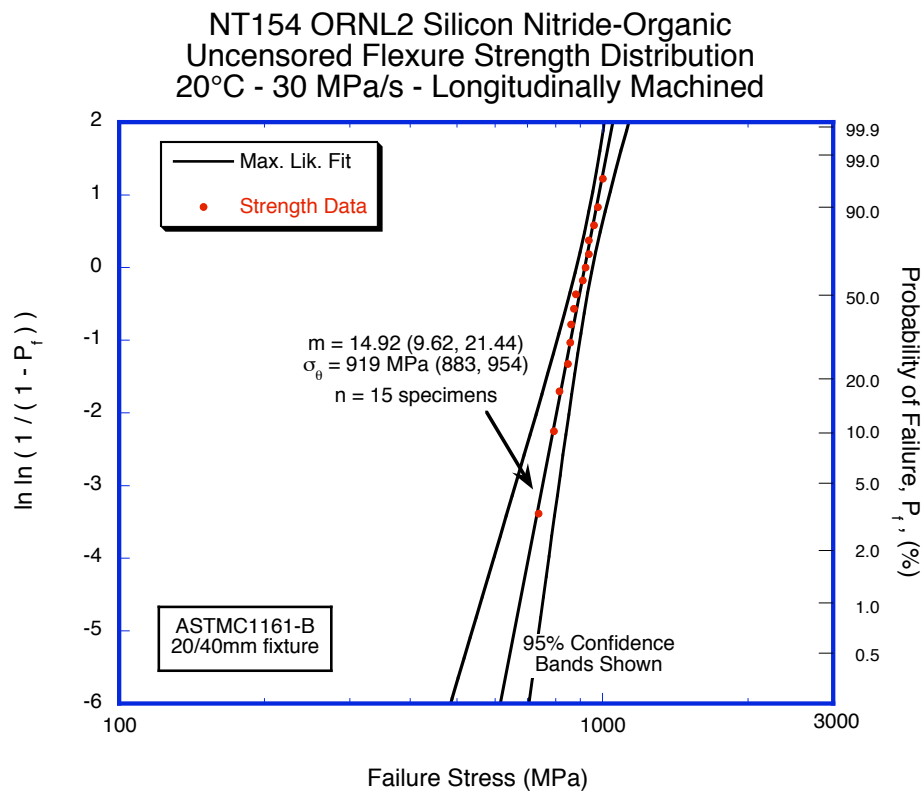




The presence of these “Si-O-N” glass pockets in the matrix might have impact on the high temperature mechanical response

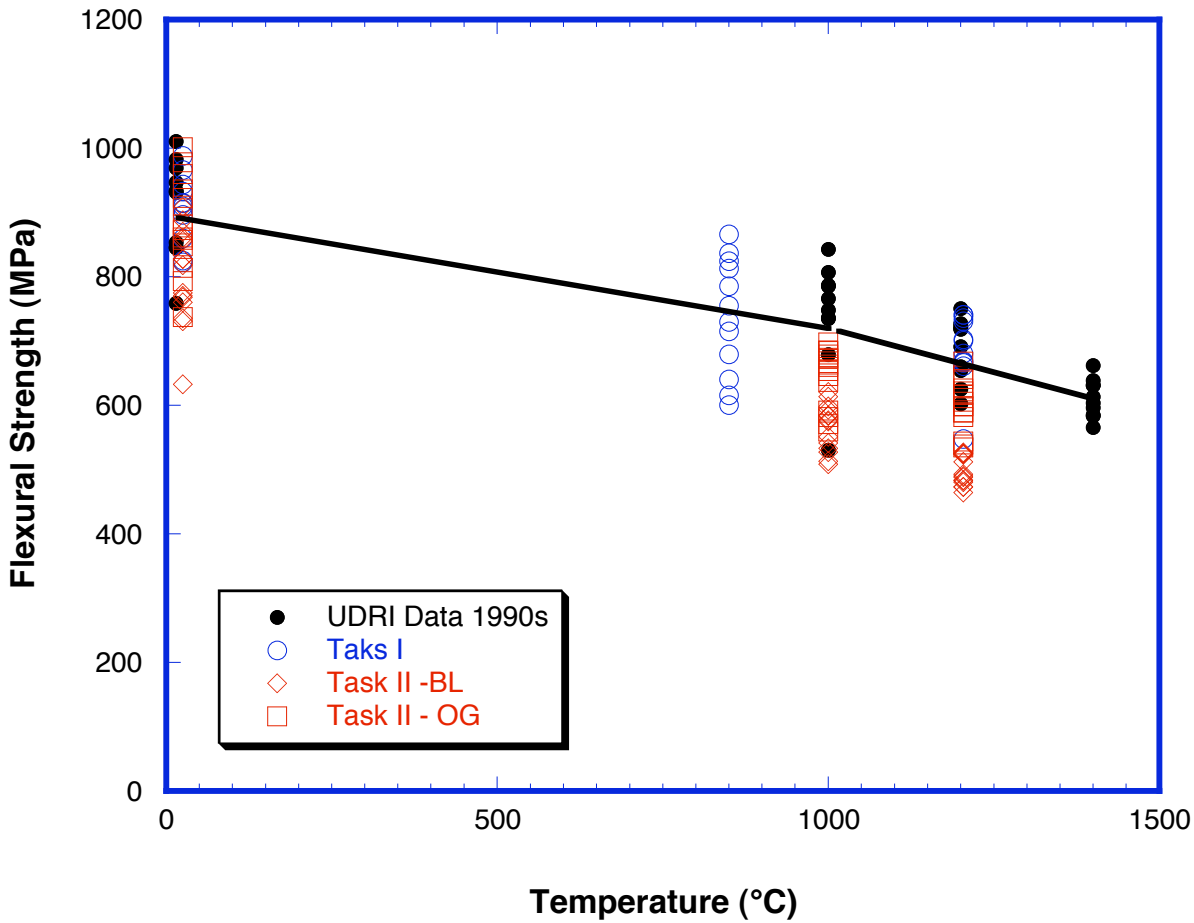
Addition of Organic Binder Increases the Characteristic Strength by ~ 10%, but with Similar Weibull Distribution





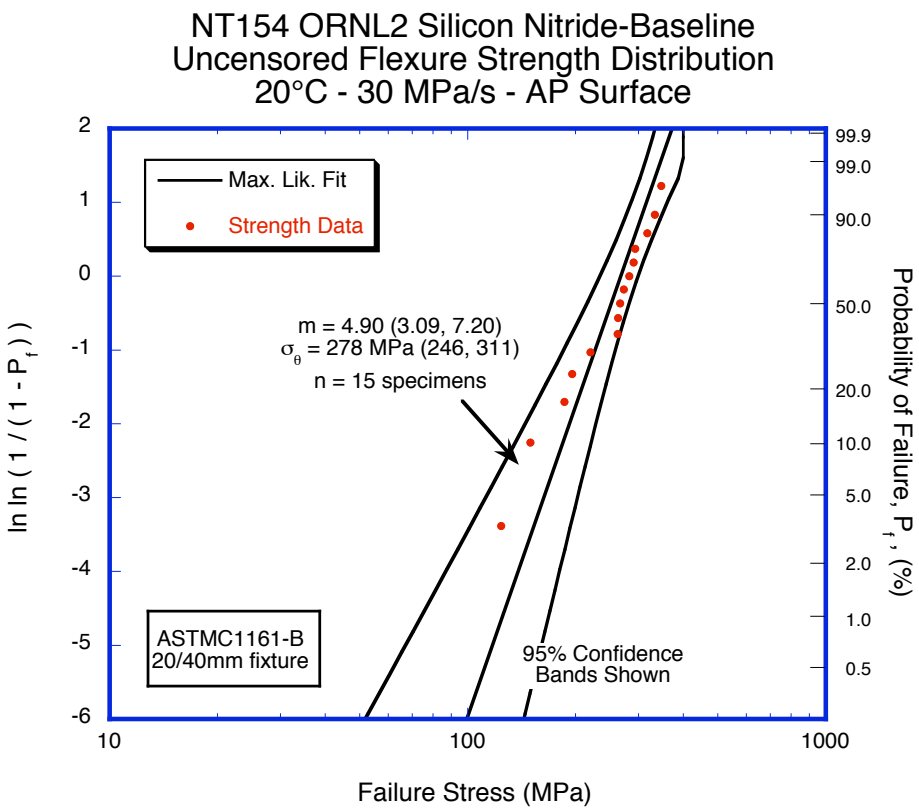
The minor improvement in characteristic strength might be related to the different matrix microstructure and elongated grain content

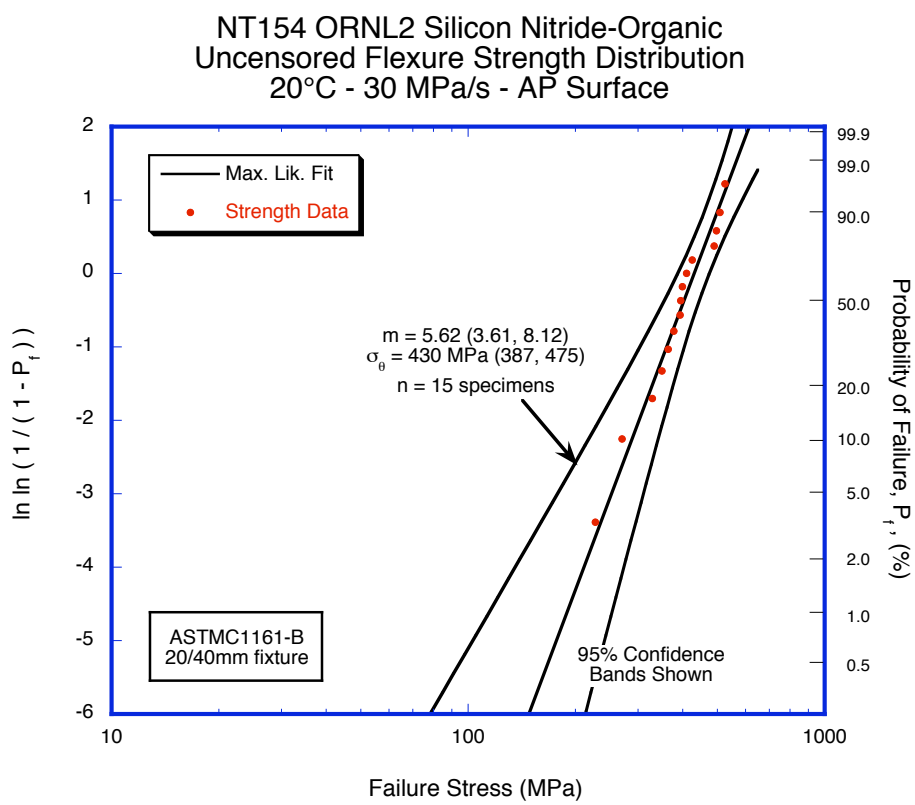
The Re-established NT154 Silicon Nitride Exhibits Comparable Mechanical Performance to Those Manufactures in 1990s



Database generated by UDRI was sponsored by DOE OTT Ceramic Technology for Advanced Heat Engine Program

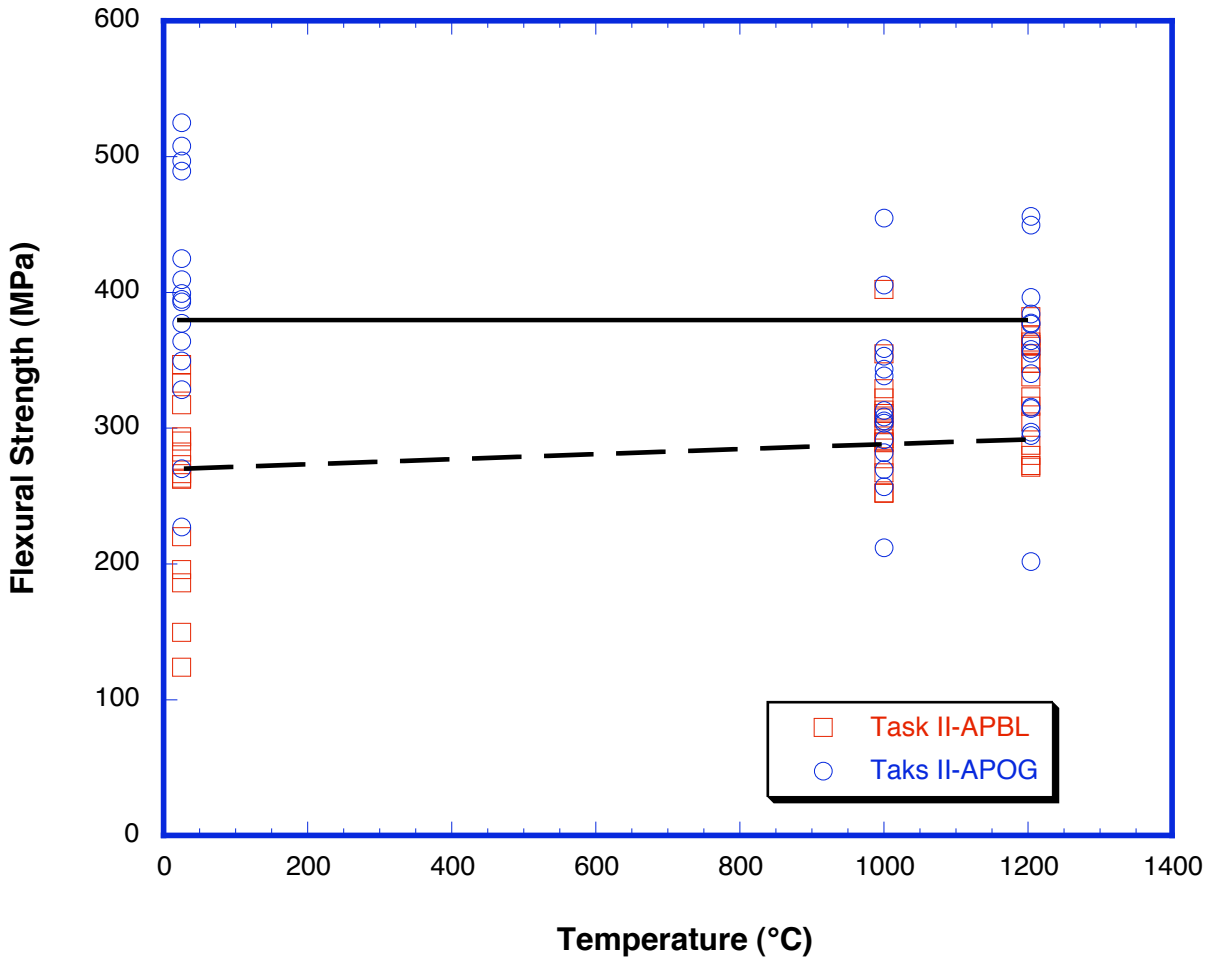
The Materials with As-Processed Surface Exhibit Poor Mechanical Properties





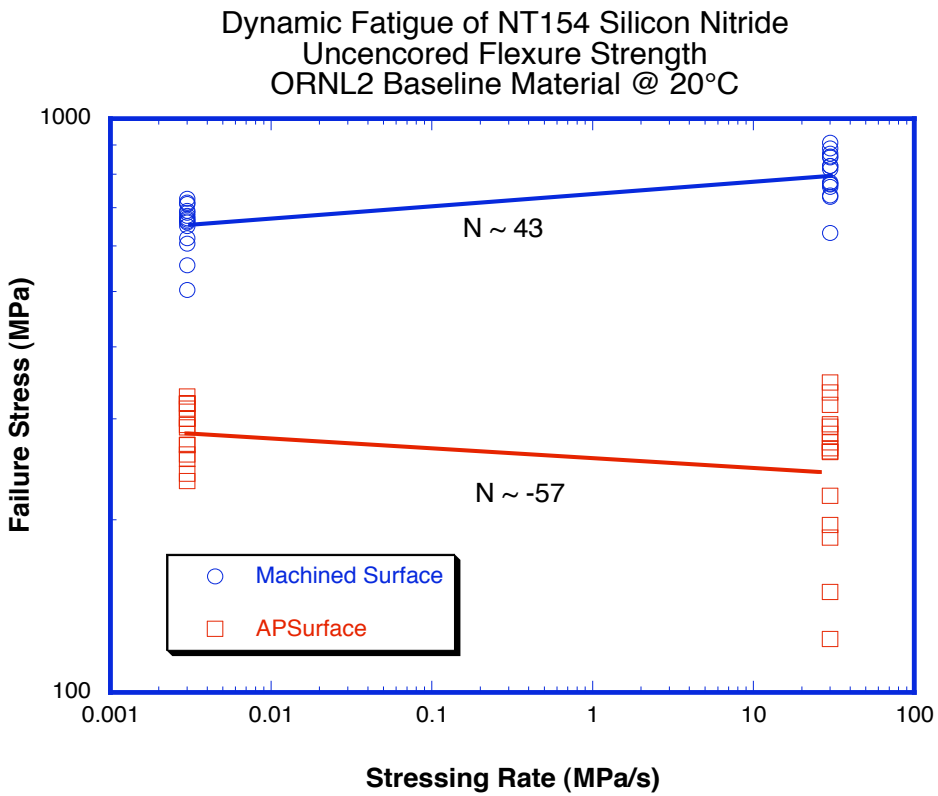
The mechanical properties of samples with as-processed surface play an important role in probabilistic component design and life prediction

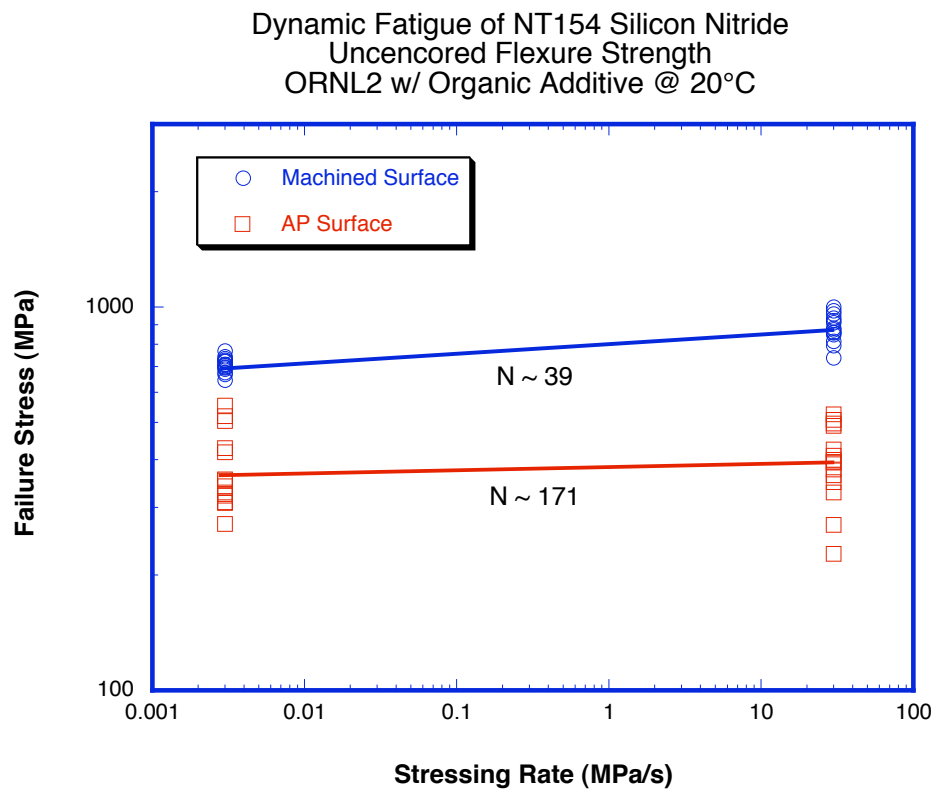
The Mechanical Properties of NT154 with As-Processed Surface are Insensitive to Test Temperature



The mechanical properties of samples with as-processed surface are probably governed by the surface flaws

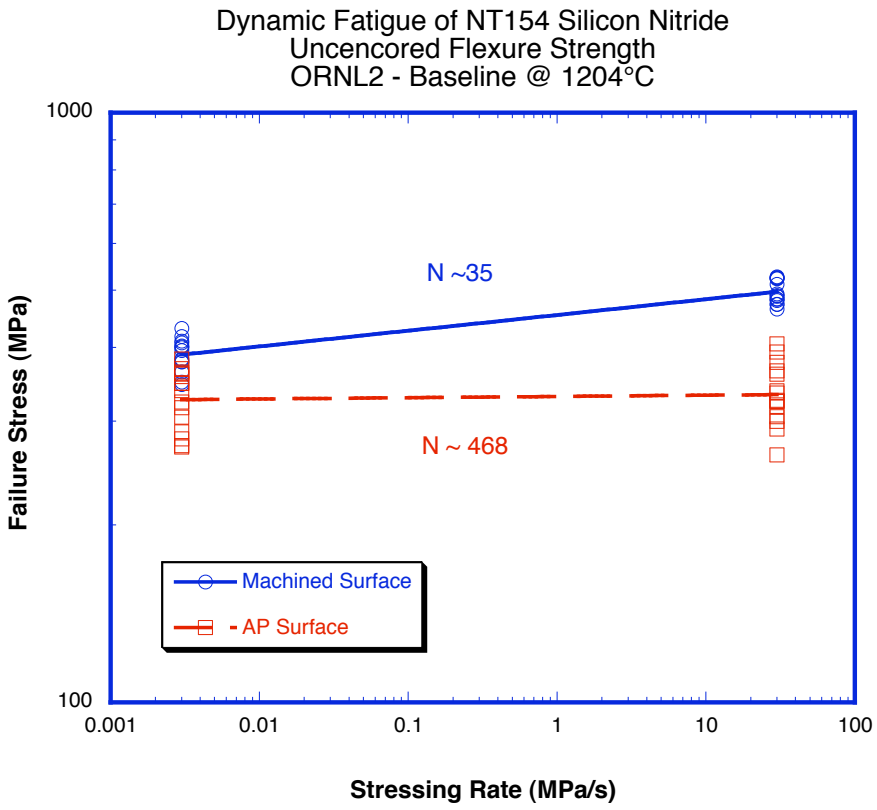
The Dynamic Fatigue Exponents Obtained are Consistent to Those Values Obtained for 1990s Materials

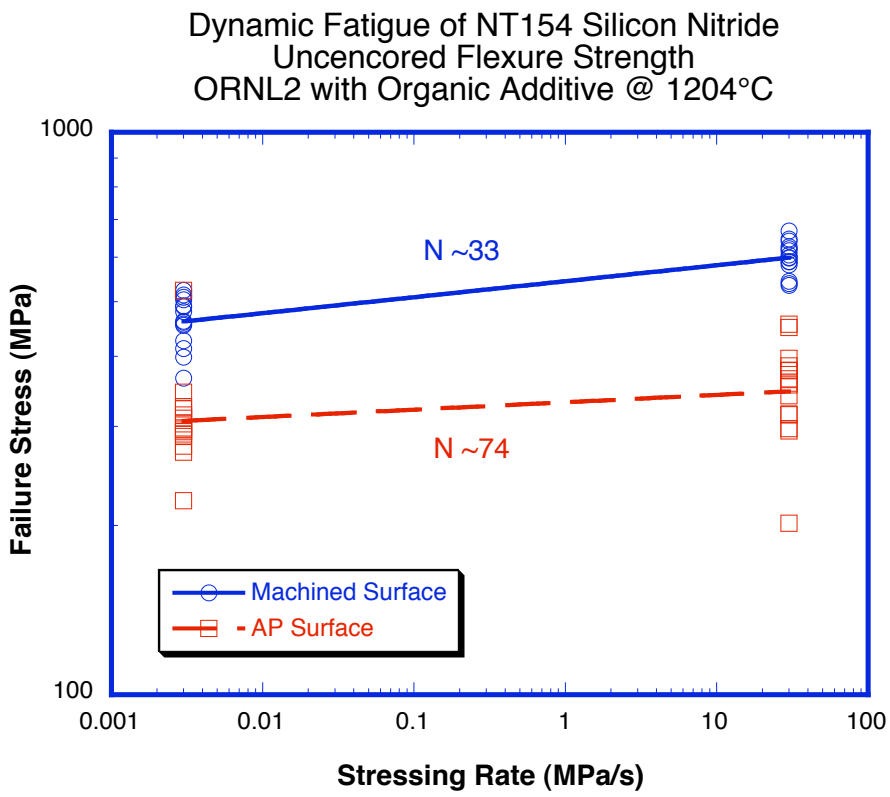




The dynamic fatigue exponent of material with AP surface would not represent the “true” mechanical performance

The Dynamic Fatigue Exponents for Bulk Materials are Insensitive to Test Temperature up to 1204°C

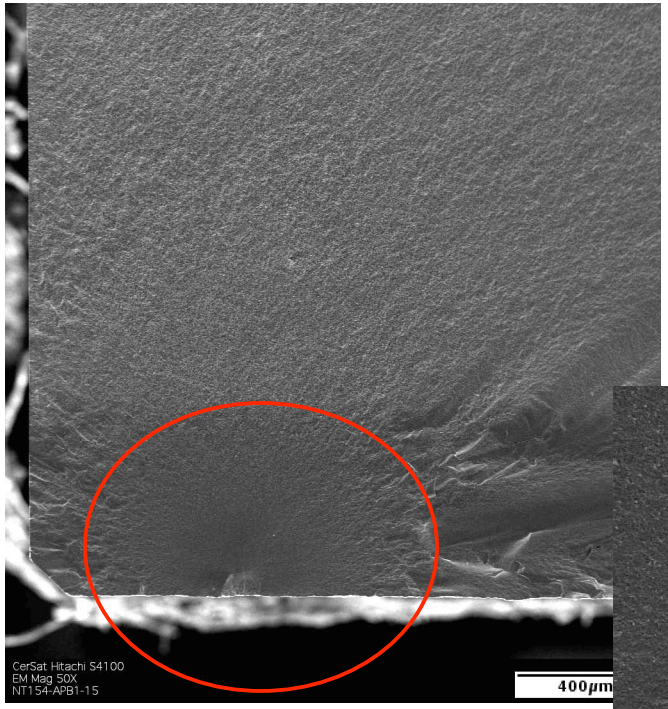


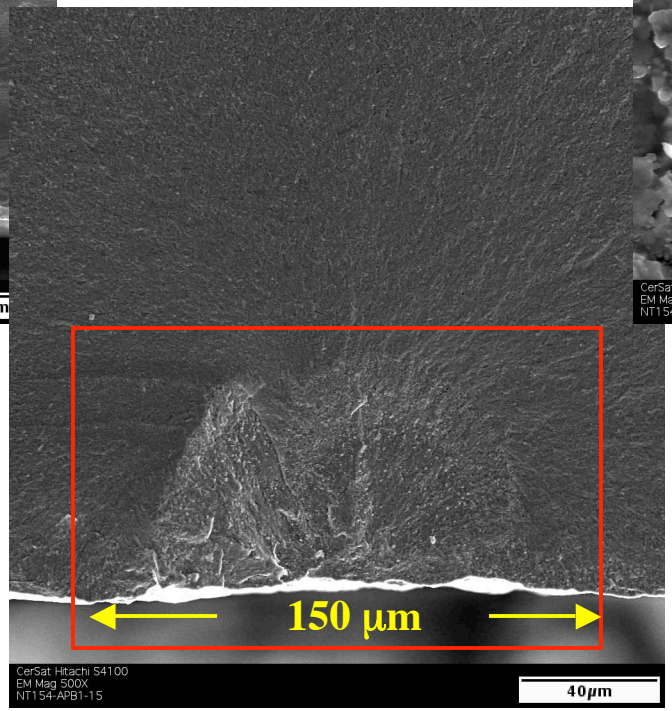


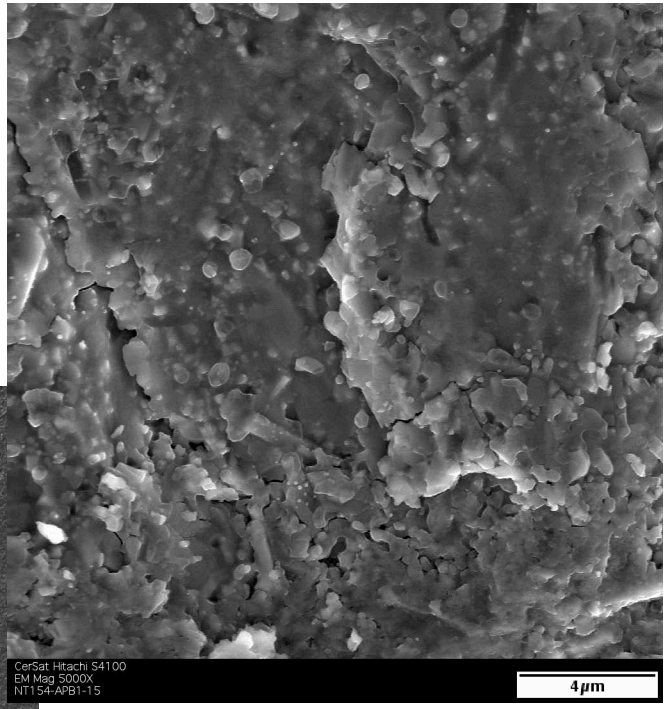
$N_{baseline} \sim 43$ (1000°C)

$N_{org} \sim 45$ (1000°C)

The Combination of Surface Flaw and Brittle Reaction Layer Causes the Low Flexural Strength of AP Material



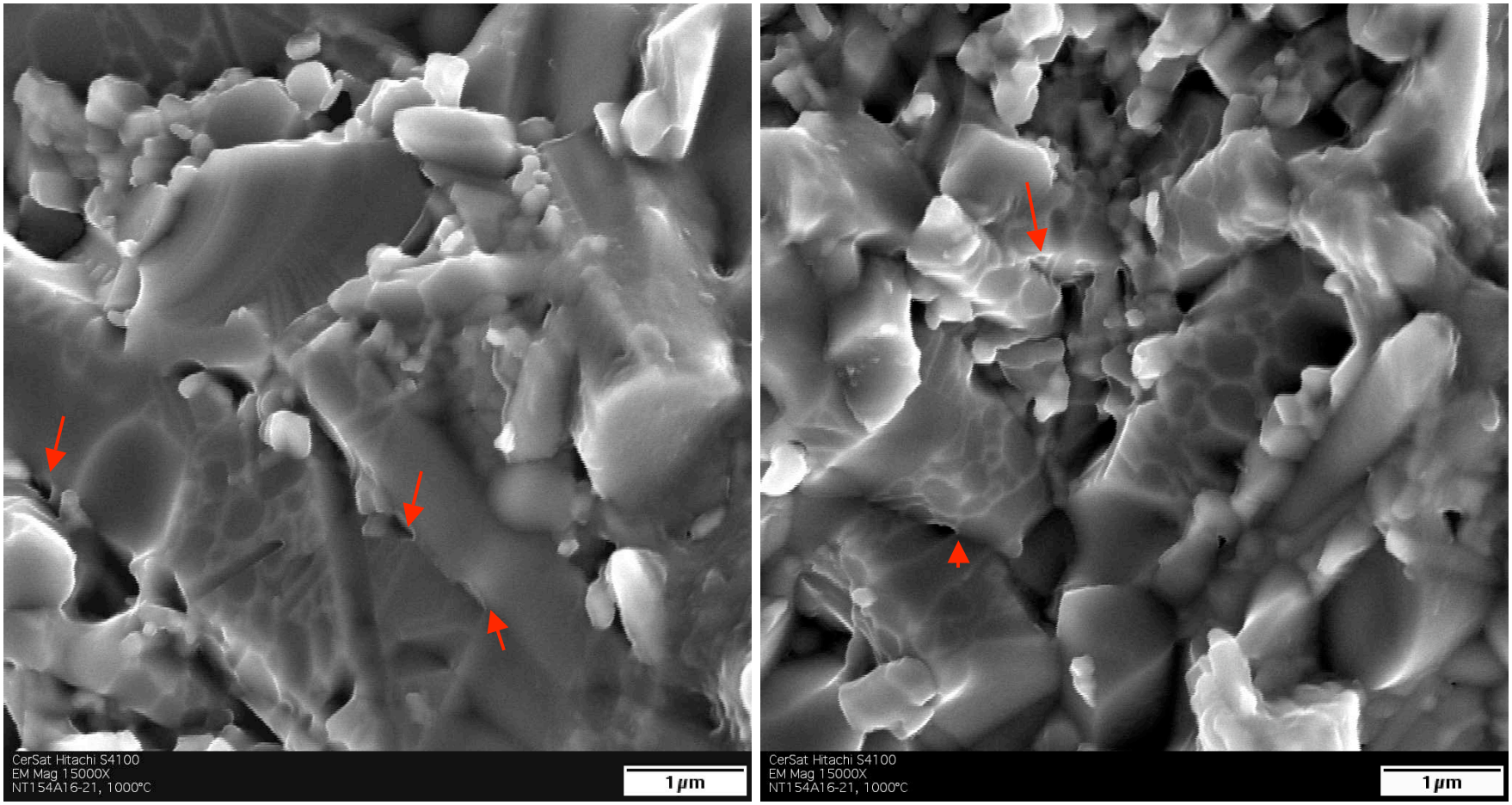




These flaw features will significantly influence the mechanical reliability of Si_3N_4 components with AP surface

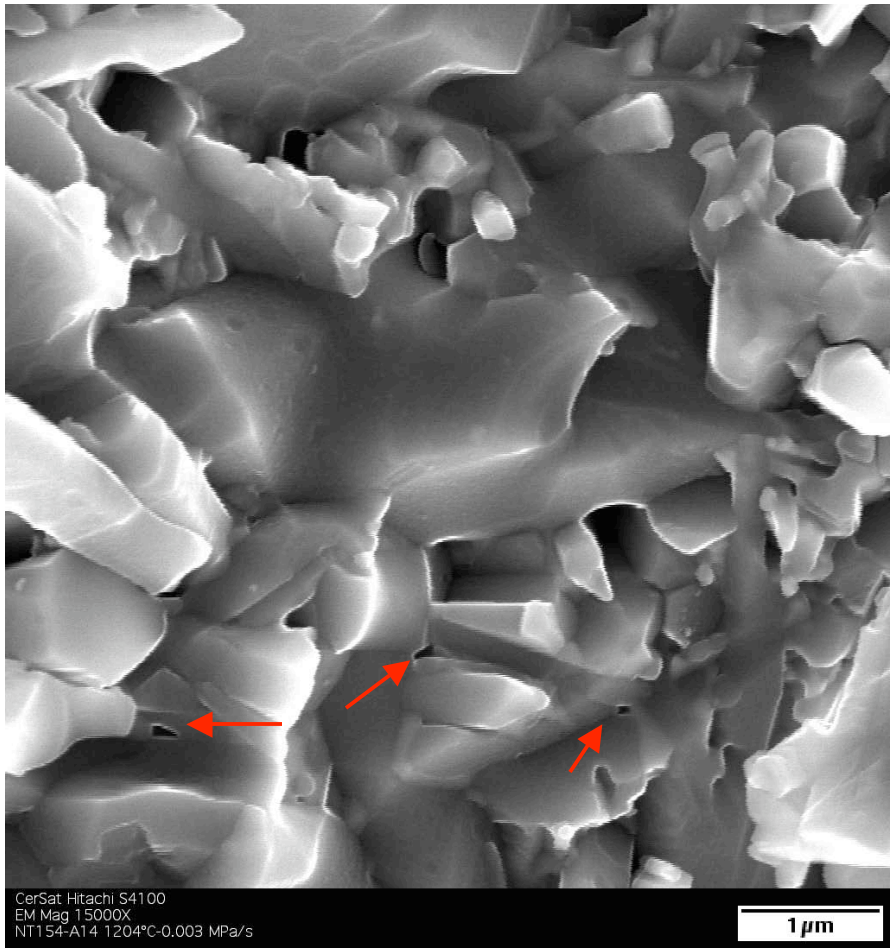
Saint-Gobain has applied a proprietary diffusion barrier coating to eliminate the surface reaction layer and improve the mechanical properties

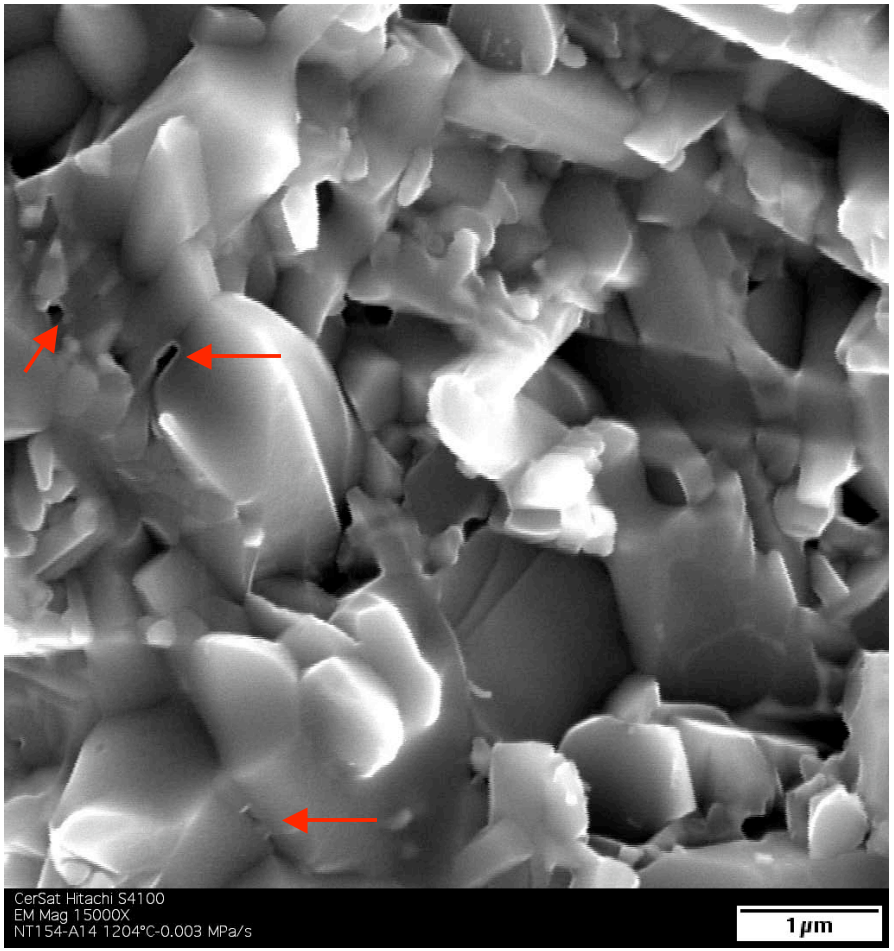
SEM Fracture Surface Features of NT154 Samples Tested @ 1000°C, 0.003 MPa/s



Viscous glass feature suggests the onset of the softening of glassy phase could occur at 1000°C

SEM Fracture Surface Features of NT154 Samples Tested @ 1200°C, 0.003 MPa/s





Observation of creep cavities consistent with the minor permanent curvature observed after flexural testing

Summary

- The advanced ceramics (Si_3N_4 and composites) are the key enabling technology to achieve the 40% efficiency and NOx reduction of microturbine engines
- The re-established NT154 exhibits comparable mechanical performance to those manufactured in 1990s
- The samples with as-processed surface exhibit poor characteristic strength and low Weibull module due to the presence of surface flaw and reaction layer
- The onset of softening of glassy phase and (maybe) creep process might be attributed to the low fatigue exponents obtained at 1000 and 1200°C
- The mechanical database of as-processed samples would have a significant impact on the components design and life prediction
- An effective diffusion barrier coating is needed to eliminate the surface reaction layer to improve the mechanical performance and reliability