Mechanical Behavior of Ceramic Materials

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PM 10459

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Oak Ridge National Laboratory
U. S. Department of Energy

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Mechanical Behavior of Ceramic Materials

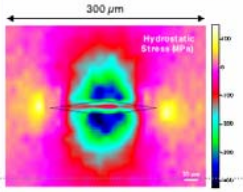
21CTP Technical Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

Project Objectives
- Enable the development of more wear-resistant and mechanically robust ceramic components through the systematic evaluation of contact damage in ceramics.

FY 2005 Focus
- Evaluate rate and grain size effects on contact damage in candidate ceramics for diesel engine components.
- Develop criterion to rank/compare damage resistance.

Planned Duration
October 2003 to September 2005

DOE Funding/Industry Cost Share
FY04: $300K; FY05: $275K



Residual stress field about region of contact damage (2kg Knoop indent) in an Al_2O_3 ceramic. Measured using optical fluorescence.

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Accomplishments
- Established dynamic indentation and instrumented scratch testing facilities.
- Co-developed and copyrighted *μ-FEA* software that facilitates microstructural stress analysis.

Significant Future Milestones
- Develop a generic FEM that predicts the onsets of quasi-plasticity and fracture/cracking in any target material as a function of indentation load, indenter material, friction, and confinement. (9-05)

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_10459	Materials Technology	HV Propulsion Materials	Applied Research	8-15-05

Objectives

- **Study rate effects on deformation processes in Si_3N_4**
- **Why?**
  - **Deformation processes in Si_3N_4 ceramics are linked to their machinability (i.e., cost of manufacture) and resistance to contact damage in components (i.e., performance)**
  - **Si_3N_4 ceramics are of strong interest for diesel engine roller elements; however, not much is known about how Si_3N_4 ceramics respond when analyzed at fast rates**
- **Develop supplemental models to assist in deformation interpretation**

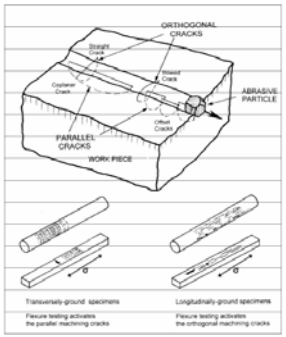


Image from:
"On the Fractographic Analysis of Machining Cracks in Ground Ceramics: A Case Study on Silicon Nitride," G. D. Quinn, L. K. Ives, and S. Jahanmir, NIST Special Pub. 996, 2003.

Approach

- **Characterize damage processes in Si_3N_4 ceramics through static and dynamic indentation**
- **Develop criterion that can be used to rank resistance to damage**
- **Evaluate relevant Si_3N_4 grades (e.g., existing commercial roller element and ball bearing compositions, standard reference materials)**
- **Evaluate grain size effects on damage processes through static and dynamic indentation (model Al_2O_3 ceramics)**

Relevance to 21 CT Goals

21CTP Technology Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

The substituted use of ceramic components (e.g., roller elements, exhaust valves, valve seats, fuel system components) in diesel engines could enable

- **Higher thermal efficiency**
- **Longer characteristic life**
- **Reduction in parasitic losses**
- **Reduced weight**

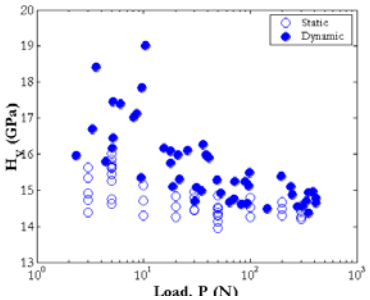
Accomplishments

- **Established dynamic indentation and instrumented scratch testing facilities**
- **A new brittleness parameter was developed that represents static and dynamic indentation responses**
- **Developed a FEM that predicts the onsets of quasi-plasticity and fracture/cracking as a *f*(P, indenter material, friction, and confinement)**
- **Co-developed and copyrighted *μ-FEA* software**

Dynamic Indenter

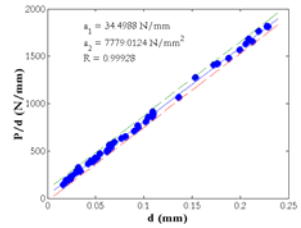
Instrumented Scratch Tester

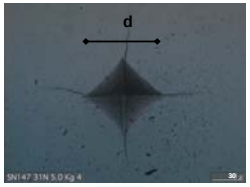
All Five Si_3N_4 Exhibited Higher Hardness at Faster Rates

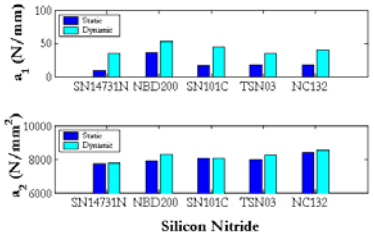


- Ceralloy 147-31N, Ceradyne, SRBSN
- NBD 200, Cerbec, HIP
- SN101C, Cerbec, HIP
- TSN 03-NH, Toshiba, HIP
- NC132, Norton, HPSN

Static vs. Dynamic Responses in Si_3N_4



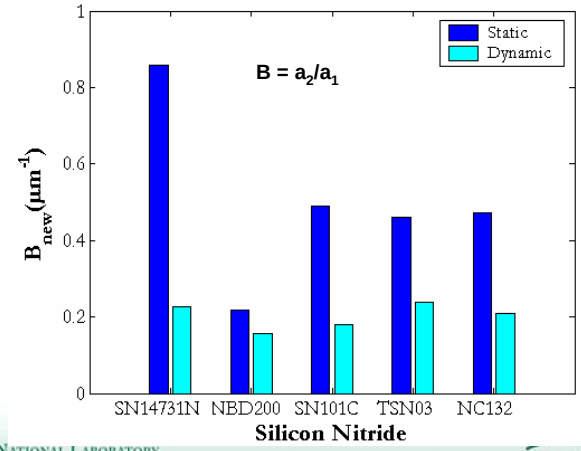




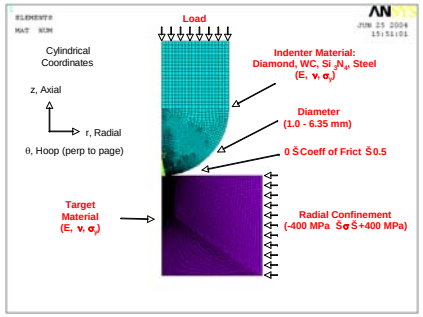
PSR Model (Bernhardt, 1941)

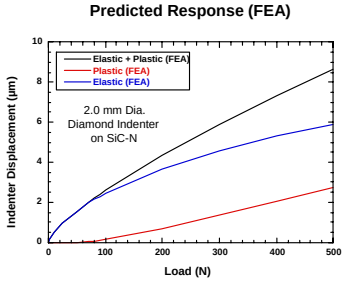
$P = a_1 d + a_2 d^2$ => $P/d = a_1 + a_2 d$

A New Brittleness Parameter Shows That All the Silicon Nitrides Were Less Brittle at Faster Rates

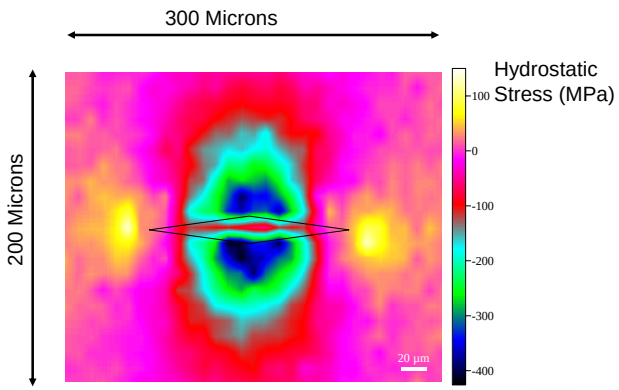


A Finite Element Model Was Developed to Interpret Quasi-plasticity and Fracture Processes





Optical Fluorescence is Being Used to Examine Residual Stress Fields and Interpret Damage



µ-FEA Was Developed - What Does It Do?

- **Enables a user to capture the complexity of (real) microstructures though simple, quick input of digital SEM and OM images**
- **Enables a user to examine and interpret resulting stresses from the FEA model or easily compare stress fields**
- **Because ANSYS is used as the FEA Solver, the full multi-physics suite of ANSYS features is exploitable:**
  - **Linear and non-linear material properties**
  - **Steady-state and transient analysis (e.g., creep, viscous deformation, etc.)**
  - **Thermomechanical analysis (e.g., thermal shock, etc.)**
  - **Piezoelectric analysis**
  - **Phase changes and swelling**
  - **Element kill and death**
  - **Probabilistic analysis (interfaced with CARES)**

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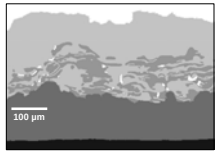
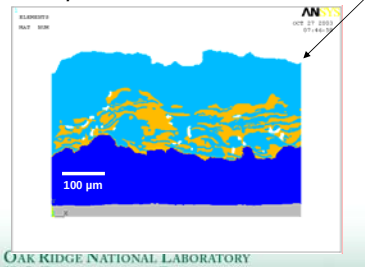
Example of Use of *μ-FEA*

Microstructural Region

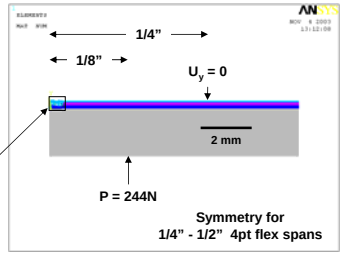


***μ-FEA* Reconstructed Model**



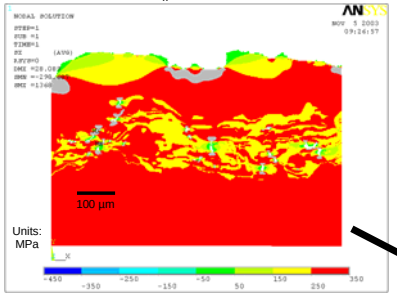
Detail

Whole Modeled Geometry

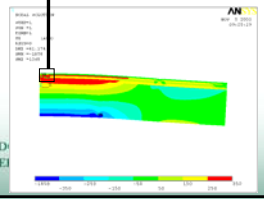


Example of *μ-FEA* Results

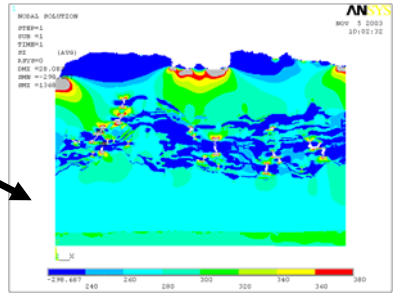
σ_x Stresses



σ_x Stresses in Whole Model



Refined View of σ_x Stresses



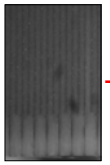
Technology Transfer

- Copyrighted µ-FEA program in FY2005
- A domestic Si_3N_4 manufacturer (Cerbec) considering using dynamic indentation to assess new Si_3N_4 compositions

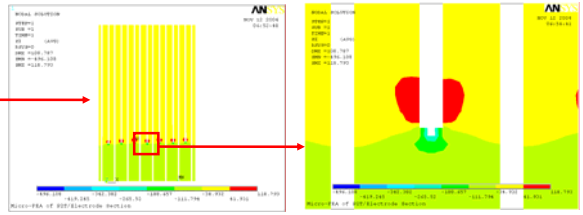
Future Work

- New project involving reliability analysis and design of piezostack fuel injector (potential CRADA with Delphi under negotiation)
- Assess grain size effect on rate and deformation process

Piezoelectric Structure



PZT Stress Field in µ-FEA Region



Publications, Presentations, Patents

- **Publications**
  - **A. A. Wereszczak and T. P. Kirkland, "Exclusivity of Strength-Limiting Extrinsic Surface and Hybrid Flaws," in press, *Ceramic Engineering and Science Proceedings* (2005).**
  - **H. Wang and A. A. Wereszczak, "Mechanical Responses of Silicon Nitrides Under Dynamic Indentation," in press, *Ceramic Engineering and Science Proceedings* (2005).**
  - **G. Subhash, M. A. Marszalek, A. A. Wereszczak, and M. J. Lance, "Evaluation of Scratch Resistance and Residual Stresses in Machined Silicon Nitride," in press, *Ceramic Engineering and Science Proceedings* (2005).**
- **Presentations**
  - **A. A. Wereszczak, "Research Overview of ORNL's Ceramic Science and Technology Group," University of Alabama, Tuscaloosa, AL, Apr. 20, 2005.**
  - **A. A. Wereszczak, "Exclusivity of Strength-Limiting Intrinsic and Hybrid Flaws," *29th Annual Conference on Composites and Advanced Ceramics*, Cocoa Beach, FL, Jan. 2005.**
  - **H. Wang, "Mechanical Responses of Silicon Nitrides Under Dynamic Indentation ," *29th Annual Conference on Composites and Advanced Ceramics*, Cocoa Beach, FL, Jan. 2005.**
  - **G. Subhash, "Evaluation of Scratch Resistance and Residual Stresses in Machined Silicon Nitride ," *29th Annual Conference on Composites and Advanced Ceramics*, Cocoa Beach, FL, Jan. 2005.**
- **Copyrights**
  - ***μ-FEA* (software), US Copyright Office registration # TXu1-234-195, CR No. 40000050, 25 April 2005.**