NATIONAL EDUCATORS' WORKSHOP
NEW: Update 91

STRUCTURAL CERAMICS

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IMPACT OF MATERIALS

IN 1982, DAMAGES DUE TO MATERIAL FAILURE WERE GREATER THAN $200 BILLION ANNUALLY - THIS APPROACHES THE ANNUAL FEDERAL DEFICIT. (M. Cohen in Advanced Materials Research, NAS/NAE, 1987)

COMPETITIVENESS AND QUALITY OF LIFE IN THIS DECADE AND 21st CENTURY WILL DEPEND UPON ADVANCES IN MATERIALS. (paraphrase of R. Chianelli, MRS Bulletin, August, 1990)

LEADERS IN MATERIALS TECHNOLOGY WILL DOMINATE THE MARKETPLACE IN THE 21st CENTURY. (Panel discussion at Int'l Symp. Basic Technologies for Future Industries, Kobe, Japan, March 1989)
COMMODITY METALS AND PLASTICS HAVE PASSED DEMAND PEAK AND USAGE IS DECLINING
THERE IS A CHANGE IN BASIC MATERIAL USE

- SUBSTITUTION OF ONE MATERIAL FOR ANOTHER HAS SLOWED THE GROWTH OF DEMAND FOR PARTICULAR MATERIALS

- DESIGN CHANGES HAVE INCREASED THE EFFICIENCY OF MATERIALS USE

- SATURATION OF MARKETS WHICH WERE PREVIOUSLY EXPANDING HAS OCCURRED

- LOW MATERIALS CONTENT IN PRODUCTS FOR NEW MARKETS, PARTLY BECAUSE OF THE COST OF HIGHER PERFORMANCE MATERIALS
MARKET DEMAND IS NOW LIGHTER, STRONGER, MORE DURABLE MATERIALS

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<tbody>
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(Materials Science and Engineering for the 1990s)
MODERN MATERIALS 50X HIGHER
STRENGTH-TO-DENSITY RATIO THAN CAST IRON
MODERN MATERIALS ENABLE HIGHER ENGINE OPERATING TEMPERATURES

![Graph showing the increase in engine operating temperature from 1900 to 1980. The graph indicates that modern turbojet engines can operate at higher temperatures than steam engines and air-cooled aircraft engines.]
MATERIALS ENABLED EXPONENTIAL INCREASE IN CUTTING TOOL SPEED

![Graph showing the exponential increase in cutting tool speed over time. The graph plots cutting speed (in/min) against year. The cutting tools are labeled as Tool steel, WC, Ceramic, and BN, Diamond, with the cutting speed increasing significantly over time.]
THE PORTFOLIO OF ADVANCED MATERIALS

CERAMICS

CMC

REINFORCEMENTS

PMC

MMC

POLYMERS

METALS
STRUCTURAL CERAMICS ARE LEADING CANDIDATES FOR MANY APPLICATIONS

CERAMICS
Inorganic, nonmetallic materials processed or consolidated at high temperatures

TRADITIONAL
Based primarily on natural raw materials of clay and silicates
- Clay products
- Glass
- Cement

ADVANCED*
Include artificial raw materials, exhibit specialized properties, require more sophisticated processing
- Structural
- Electronic
- Optical

* Fine ceramics, Engineered ceramics, New ceramics, Value-added ceramics
THE APPEAL OF STRUCTURAL CERAMICS IS EASY TO UNDERSTAND

<table>
<thead>
<tr>
<th>Desired Characteristic</th>
<th>Light with compressive strength &gt; or = metals</th>
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<tbody>
<tr>
<td>Light / strong</td>
<td>Withstand extreme temperatures</td>
</tr>
<tr>
<td>High temp resist.</td>
<td>Chemically inert, hard, abrasion resistant</td>
</tr>
<tr>
<td>Corrosion resist.</td>
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<td>Efficient processing</td>
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BUT REALIZING THESE PROPERTIES REQUIRES A LEVEL OF MICROSTRUCTURAL AND CHEMICAL PERFECTION FAR BEYOND THAT OF TRADITIONAL CERAMICS
### Structural Ceramics Are a Result of a Few Key Developments

<table>
<thead>
<tr>
<th>Traditional</th>
<th>Development</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>Synthetic Materials Preparation</td>
<td>Synthetic (Contrived)</td>
</tr>
<tr>
<td>Optical, Macro</td>
<td>XRD, Electron Microscopy</td>
<td>Micro-analysis</td>
</tr>
<tr>
<td>Historic, Tolerant</td>
<td>Relations of Processing &amp; Properties</td>
<td>Uniform Chemistry &amp; Structure</td>
</tr>
</tbody>
</table>

1800 - 1930 - 1950 - 1990
SOPHISTICATED MICROSCOPY ALLOWS DETERMINATION OF MICROSTRUCTURE
MECHANICAL PROPERTIES CAN BE DETERMINED AT THE MICROSTRUCTURAL LEVEL
TENSILE TESTER—SPECIALIZED EQUIPMENT FOR DETERMINING CERAMIC MECHANICAL PROPERTIES
ADVANCES IN CERAMICS WILL BE BASED ON ATOMISTIC MODELING, TAILORED MICROSTRUCTURE AND SOPHISTICATED PROCESSING
TOUGHENING IS REQUIRED TO MAKE CERAMICS Viable FOR STRUCTURAL APPLICATIONS

![Diagram showing the relationship between flexure strength, toughness, and maximum flaw size for different types of materials.](image)

- Metals
- Toughened ceramics
- Current ceramics
- For C = 400 \mu m

- \( K_{IC} = 25 \text{ MPa}\sqrt{\text{m}} \)
- \( K_{IC} = 10 \text{ MPa}\sqrt{\text{m}} \)
- \( K_{IC} = 4 \text{ MPa}\sqrt{\text{m}} \)
- \( \sigma_f = 987 \text{ MPa} \) (141 ksi)
- \( \sigma_f = 395 \text{ MPa} \) (55 ksi)
- \( \sigma_f = 158 \text{ MPa} \) (25 ksi)

![Diagram showing the effect of temperature on the toughening strategy for different materials.](image)

- Whisker and fiber reinforcement
- Partially stabilized zirconia
- Monolithic ceramics

![Diagram showing the relationship between maximum flaw size and temperature for various materials.](image)
MICROSTRUCTURE TAILORING & NOVEL COMPOSITE DESIGN ADDRESS INHERENT BRITTLENESS OF CERAMICS

COMPAARED TO METALS WITH TYPICAL FRACTURE TOUGHNESS OF 15-200
FRACTURE RESISTANCE IS INCREASED BY REINFORCING CERAMICS WITH STRONG MICROSCOPIC WHISKERS

Ceramic Whiskers and Human Hair

Ceramic Composite Fracture Surface

Toughness Model

\[ dK = G^{WR} \left( \frac{V_r}{E^W} \right) \left( \frac{E^C}{6(1-V^2)} \right) \]

- \( d^{WR} \) = Fracture strength whisker
- \( V \) = Vol. fracture whiskers
- \( r \) = Whisker radius
- \( E \) = Young's modulus
- \( G \) = Fracture Energy
R&D ADDRESSING EFFECTS OF WHISKER COATINGS ON COMPOSITE PROPERTIES

Alumina-SiC whisker interface

Carbon coated whisker-alumina interface
FIBER-REINFORCED CERAMIC COMPOSITES HAVE BEEN FABRICATED USING A FORCED CHEMICAL VAPOR INFILTRATION PROCESS.
EXPERIMENTAL RESULTS SHOW MODIFICATION OF MATRIX/WHISKER INTERFACE IMPROVES COMPOSITE TOUGHNESS
TOUGH, CONTINUOUS-FIBER CERAMIC COMPOSITE
SUCCESSFUL FABRICATION BY FCVI OF ARTICLES WITH COMPLEX SHAPES AND FIBER ARCHITECTURES HAS BEEN DEMONSTRATED.

ANGLE-WOUND TUBE

REPRESENTATIVE ROTOR (cloth layup)

3-D ORTHOGONAL WOVEN DISK

THICK-TO-THIN DISK (cloth layup)
Large Scale Manufacturing of Monocoque Car Chassis at the Fibrous Materials Research Laboratory
ADDITION OF ZrO₂ TO BRITTLE CERAMICS INCREASES RESISTANCE TO CRACK PROPAGATION

- Toughening is derived from stress-induced martensitic transformation in ZrO₂ particles
  - Transformation consumes energy needed for further propagation
  - Increased volume of new phase contributes compressive forces resisting further propagation
MICROWAVE SINTERING HAS SIGNIFICANT IMPLICATIONS FOR NEW MATERIALS APPLICATIONS

- Accelerated Kinetics:
  - Sintering occurs at lower temperatures

- Significant Potential Benefits
  - Lower temperature processing
  - Finer microstructures
  - Better mechanical properties

- Advanced Materials Applications:
  - Composites from incompatible materials
  - Self-lubricating high-temperature bearings
  - Electrical materials
  - Engine components
MICROWAVE FACILITY FOR DENSIFYING CERAMICS
Microstructure of Si$_3$N$_4$-6% Y$_2$O$_3$-2% Al$_2$O$_3$ After Annealing at 1200°C for 20 hours
MICROSTRUCTURE MODIFICATION SIGNIFICANTLY IMPROVES CREEP RESISTANCE

SN-6Y2A
ANNEALING CONDITIONS: 1200°C/20 h
TEST TEMPERATURE: 1260°C
Tensile creep of NTX-154 and NT-164 at 1370°C

NTX-154 had a glass layer at most Si₃N₄/Si₃N₄ grain boundaries after creep (100 MPa, 1200 h).

No glass layer was found at NT-164 Si₃N₄/Si₃N₄ grain boundaries after creep (150 MPa, 959 h).
CERAMIC TURBOCHARGER ROTOR IN PRODUCTION VEHICLE

Nissan Motor Co. Silicon Nitride Turbocharger Rotor
EXTENDED VEHICLE TESTING OF VALVE TRAIN COMPONENTS

AUTOMOTIVE VALVE
SILICON-NITRIDE
NORTON/TRW CERAMICS

AUTOMOTIVE VALVE
SPRING RETAINER CAP
SILICON-NITRIDE
NORTON/TRW CERAMICS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH
SUMMARY

- SPECIALIZED, TECHNOLOGY-INTENSIVE, HIGH-VALUE-ADDED ADVANCED CERAMICS ARE MOVING TOWARD COMMERCIALIZATION TO FILL THE DEMAND FOR LIGHTER, STRONGER, MORE CORROSION RESISTANT MATERIALS

- ADVANCEMENTS WILL RELY MORE AND MORE ON PROCESSING AND MODELING FROM THE ATOMIC SCALE UP WHICH IS MADE POSSIBLE BY ADVANCED ANALYTIC, COMPUTER, AND PROCESSING TECHNIQUES

- SPECIALIZED PROPERTIES AND HIGHER COST WILL PROVIDE BOTH NEW OPPORTUNITIES AND CHALLENGES TO DESIGNERS AND END-USERS
  - MORE RIGOROUS DEFINITION OF COMPONENT REQUIREMENTS
  - COMPONENT REDESIGN TO ACCOMMODATE BRITTLE BEHAVIOR
  - SYSTEM REDESIGN TO MAKE FULL USE OF NEW MATERIALS
  - CLOSER COUPLING BETWEEN DESIGNERS AND MATERIALS DEVELOPERS