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

COMMODITY PLASTICS
STAINLESS STEEL
SUPERALLOYS
SPECIALTY METALS
ENG. PLASTICS
ADVANCED PMCs
STRUCTURAL CERAMICS

HEAVY R&D RAPID GROWTH GROWTH maturing=GDP GROWTH < GDP

ALUMINUM COPPER CARBON STEEL
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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(Materials Science and Engineering for the 1990s)
MODERN MATERIALS 50X HIGHER STRENGTH-TO-DENSITY RATIO THAN CAST IRON

![Graph showing the strength to density ratio of various materials over time.

- Wood, stone
- Bronze
- Cast iron
- Steel
- Aramid & carbon fibers

Year:
- 1800
- 1900
- 2000

Strength/density (in., x10^6)
MODERN MATERIALS ENABLE HIGHER ENGINE OPERATING TEMPERATURES

![Graph showing the increase in engine operating temperature from 1900 to 1980. The graph indicates a significant increase in temperature over time, with labels for different types of engines: Steam Engine, Air-cooled Aircraft Engine, and Modern Turbojet.]
MATERIALS ENABLED EXPONENTIAL INCREASE IN CUTTING TOOL SPEED

![Graph showing exponential increase in cutting tool speed over time.](image)
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>
<th>Withstand extreme temperatures</th>
<th>Chemically inert, hard, abrasion resistant</th>
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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.

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<tr>
<th>MATERIALS</th>
<th>TRADITIONAL</th>
<th>DEVELOPMENT</th>
<th>ADVANCED</th>
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<tr>
<td>ANALYSIS</td>
<td>NATURAL</td>
<td>SYNTHETIC MATERIALS PREPARATION</td>
<td>SYNTHETIC (CONTRIVED)</td>
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<td>PROCESSING</td>
<td>OPTICAL, MACRO</td>
<td>XRD, ELECTRON MICROSCOPY</td>
<td>MICRO-ANALYSIS</td>
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<td>HISTORIC, TOLERANT</td>
<td>RELATIONS OF PROCESSING &amp; PROPERTIES</td>
<td>UNIFORM CHEMISTRY &amp; STRUCTURE</td>
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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
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

\[ dK = \sigma^w \frac{V_r}{6(1-V^2)} \frac{E^C}{E^W} \frac{G^M}{G^W} \]

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

Alumina-SiC whisker interface

Carbon coated whisker-alumina interface
SILICON CARBIDE WHISKER-TOUGHENED ALUMINA CERAMICS
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
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)
CERAMICS TESTED IN AEROSPACE APPLICATIONS
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 $\text{Si}_3\text{N}_4$-6\% $\text{Y}_2\text{O}_3$-2\% $\text{Al}_2\text{O}_3$ After Annealing at 1200°C for 20 hours

Conventional Heating

Microwave Heating
MICROSTRUCTURE MODIFICATION SIGNIFICANTLY IMPROVES CREEP RESISTANCE

SN-6Y2A
ANNEALING CONDITIONS: 1200°C/20 h
TEST TEMPERATURE: 1260°C

STRESS (MPa)

TIME (h)

0 20 40 60 80 100 120 140

0 50 100 150 200 250 300

0 400 800 1200 1600 2000 2400

CA AF MA
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).
GELCASTING
A NEW CERAMIC FORMING PROCESS

OBJECTIVE:
Develop low cost, high quality forming process
- Complex shapes
- Large sections
- High yields
- Near-net shape
- Scalable to high volume production

APPROACH:
Gelcasting: A process method of fabricating ceramic bodies by adding polymerizable organic ingredients to a suspension of ceramic powders in order to obtain a processable casting and solidification process.
- Ceramic powders
- Polymer
- Monomers
- Dispersants

PROCESS FLOW CHART

PROCESS APPLICATIONS

TECHNOLOGY TRANSFER AND COMMERCIALIZATION

List of materials gelcast:
- Alumina
- SiC microsphere
- Silicon carbide
- Zirconia
- Fused silica
- Bauxite
- Composites
- Aramid fiber reinforced matrix-based silicon nitride
- Alumina composites

Office of Transportation Technologies
- Base Technology Development
- Automotive Applications

Company
- Composites
- Alumina
- Silicon carbide
- Zirconia
- Fused silica
- Bauxite
- Composites

Applications
- Specialty Products
- Structural Engine Parts
- Composite Materials & Systems
- Heat Exchangers
- Pressure Vessels
- Fuel nozzles
- Partitions
- Specialty Products

Office of Industrial Technologies
- Continuous Casting
- Steel/Metal Matrix Applications

Technology Transfer

Companies interested in Gelscast Commercialization
CERAMIC TURBOCHARGER ROTOR IN PRODUCTION VEHICLE

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

AUTOMOTIVE VALVE
STEEL CON METHOD
NORTON/TRW CERAMICS

AUTOMOTIVE VALVE
SPRING RETAINER COP
STEEL CON METHOD
NORTON/TRW CERAMICS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH
CHRYSLER 2.2L ENGINE ROLLER FOLLOWER

NEEDLE BEARINGS

STEEL ROLLER

WITH STEEL ROLLER

WITH CERAMIC ROLLER

CERAMIC ROLLER
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