NATIONAL EDUCATORS' WORKSHOP
NEW: Update 91

STRUCTURAL CERAMICS

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Oak Ridge National Laboratory

November 12-14, 1991
PERSPECTIVES ON WHERE MATERIALS ARE GOING


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
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

Strength/density (in., x10^6)

YEAR

1800 1900 2000

Wood, stone  Bronze  Cast iron  Steel

Aramid & carbon fibers  Composites
MODERN MATERIALS ENABLE HIGHER ENGINE OPERATING TEMPERATURES

![Graph showing the increase in engine operating temperature over time, with labels for Steam Engine, Air-cooled Aircraft Engine, and Modern Turbojet.](image-url)
MATERIALS ENABLED EXPONENTIAL INCREASE IN CUTTING TOOL SPEED
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 $&gt; \text{ or } = \text{ metals}$</th>
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<tr>
<td>Light / strong</td>
<td>Withstand extreme temperatures</td>
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<td>High temp resist.</td>
<td>Chemically inert, hard, abrasion resistant</td>
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<td>Corrosion resist.</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

TRADITIONAL + DEVELOPMENT = ADVANCED

<table>
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<tr>
<th>MATERIALS</th>
<th>TRADITIONAL</th>
<th>DEVELOPMENT</th>
<th>ADVANCED</th>
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<td>XRD, ELECTRON MICROSCOPY</td>
<td>MICRO-ANALYSIS</td>
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<td>PROCESSING</td>
<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

![Graph showing toughness vs. flaw size and temperature]

**Maximum Flaw Size (x10^-3 in.)**

- **Metals:** $K_C = 25 \text{ MPa}\sqrt{\text{m}}$
- **Toughened Ceramics:**
  - $K_C = 10 \text{ MPa}\sqrt{\text{m}}$
  - $\sigma_t = 987 \text{ MPa} \quad (141 \text{ ksi})$
- **Current Ceramics:**
  - $K_C = 4 \text{ MPa}\sqrt{\text{m}}$
  - $\sigma_t = 395 \text{ MPa} \quad (55 \text{ ksi})$
- **For $C = 400 \mu\text{m}$**
  - $\sigma_t = 158 \text{ MPa} \quad (25 \text{ ksi})$

**Toughness (MPa$\sqrt{\text{m}}$)**

- **Whisker and Fiber Reinforcement**
- **Partially Stabilized Zirconia**
- **Monolithic Ceramics**

**Temperature (°C)**

- 0 to 1000
MICROSTRUCTURE TAILORING & NOVEL COMPOSITE DESIGN ADDRESS INHERENT BRITTLENESS OF CERAMICS

COMPARSED 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

\[ dK = \sigma^w \left( \frac{V_r \ E^c}{6(1-V^2)} \right) \ \frac{W^c}{E^w \ G^m} \]

- \( d^w = \) 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
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.
CERAMICS TESTED IN AEROSPACE APPLICATIONS
Large Scale Manufacturing of Monocoque Car Chassis at the Fibrous Materials Research Laboratory
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

Graphs showing the density of sintered materials at different temperatures and microwave frequencies.
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
Tensile creep of NTX-154 and NT-164 at 1370°C

NTX-154 had a glass layer at most \( \text{Si}_3\text{N}_4/\text{Si}_3\text{N}_4 \) grain boundaries after creep (100 MPa, 1200 h).

No glass layer was found at NT-164 \( \text{Si}_3\text{N}_4/\text{Si}_3\text{N}_4 \) grain boundaries after creep (150 MPa, 959 h).
GELCASTING
A NEW CERAMIC FORMING PROCESS

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

APPROACH:
Gelcasting: A generic method of fabricating ceramic molds byinker-polymerizing organic ingredients to a suspension of ceramic powders in order to obtain a castable casting and solidification process.
- Ceramic powders
- Solution
- Monomer
- Dispersant

PROCESS FLOW CHART

PROCESS APPLICATIONS
List of materials gelcasting:
- Alumina
- Graphite
- Silicon carbide
- Zirconia
- Fused silica
- Bakelite
- Composites
- Alumina fiber-reinforced and silicon carbide matrix
- Aloxite composites

TECHNOLOGY TRANSFER AND COMMERCIALIZATION

Office of Transportation Technologies
Base Technology Development
- Aeronautics Applications

Office of Industrial Technologies
Continuous Gelcasting
- Aeronautics Applications

Companies interested in Gelcasting Commercialization
- Boeing
- NASA
- Partnership
- General Electric

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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
CHRYSLER 2.2L ENGINE ROLLER FOLLOWER

WITH STEEL ROLLER

WITH CERAMIC ROLLER

NEEDLE BEARINGS

STEEL 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 COSTWill 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