Chapter 14: Properties and Applications of Ceramics

Mechanical Properties of Ceramics

Brittle Fracture

- Ceramics failed by brittle fracture
- It fails without the formation of necking or any plastic deformation
- The process of brittle fracture consist of the formation and propagation of cracks through the cross section of material in a direction perpendicular to the applied load
- Crack growth through grains, specific crystallographic planes and planes of high density

Mechanical Properties

- Ceramic materials are more brittle than metals.
  Why is this so?

Bond type

- The atoms in ceramic materials are most commonly held together by the two covalent and ionic primary bonds (or) mix of them. Covalent and ionic bonds are much stronger than metallic bonds.

Consider mechanism of deformation

  – In crystalline, by dislocation motion
  – In highly ionic solids, dislocation motion is difficult
    - few slip systems

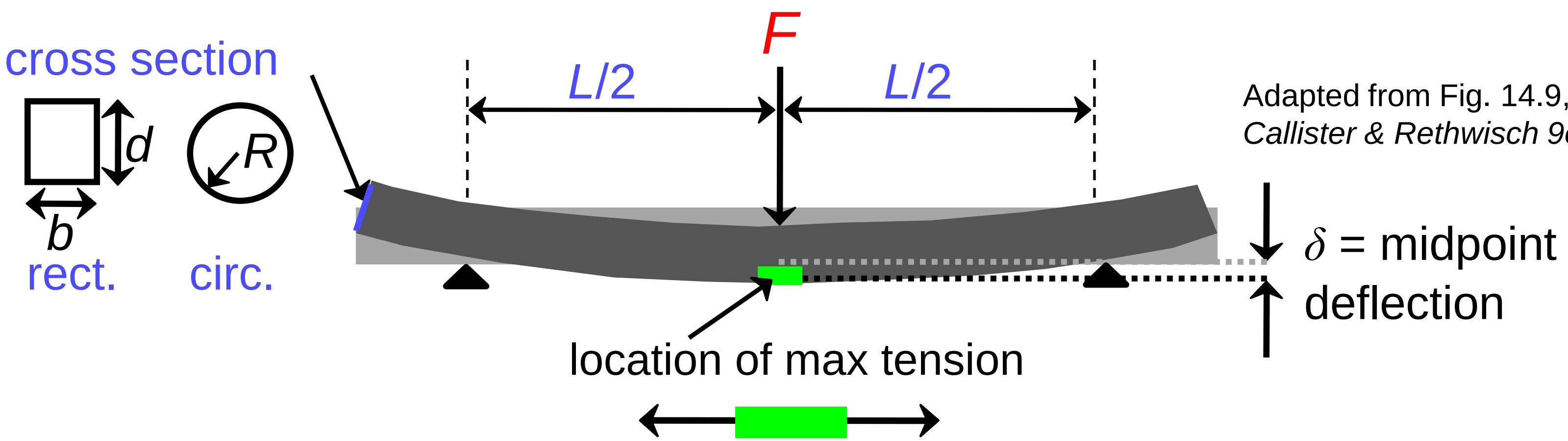
      Slip systems: Both these bond types have a very few/limited slip systems (crystallographic planes and directions within those planes) as a consequence dislocations are limited and results in a negligible or no plastic deformation at room temperature

    - resistance to motion of ions of like charge (e.g., anions) past one another

Flexural Tests – Measurement of Flexural Strength

- Room T behavior is usually elastic, with brittle failure
- Cannot use typical tensile test as metals.
- 3-Point Bend Testing often used.

- 3-point bend test to measure room-T flexural strength.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Flexural strength:

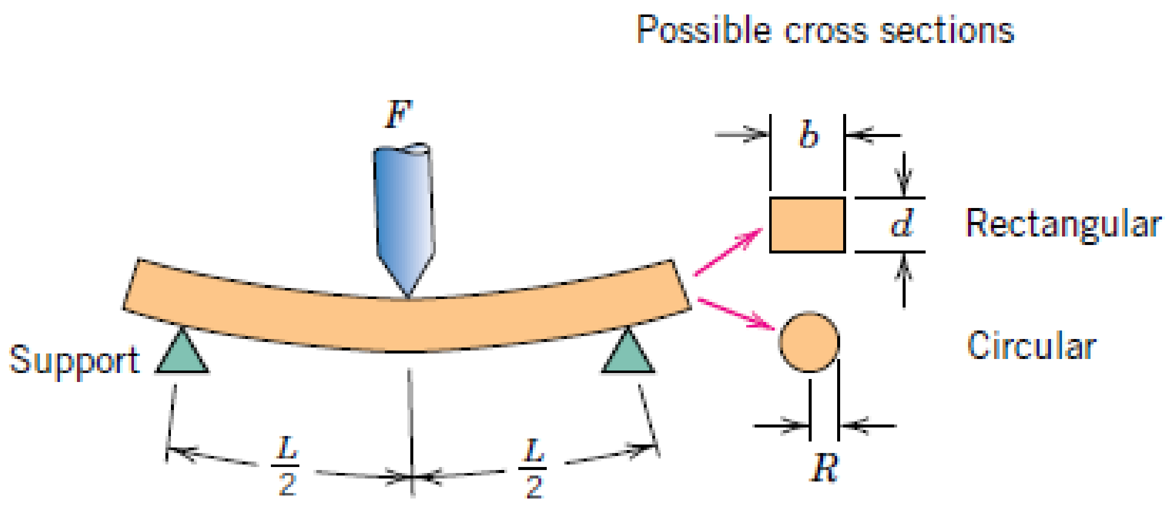
$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \quad \text{(rect. cross section)}$$

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \quad \text{(circ. cross section)}$$

- Typical values:

Material	σ_{fs} (MPa)	E(GPa)
Si nitride	250-1000	304
Si carbide	100-820	345
Al oxide	275-700	393
glass (soda-lime)	69	69

Data from Table 14.1, *Callister & Rethwisch 9e.*



$$\sigma = \text{stress} = \frac{Mc}{I}$$

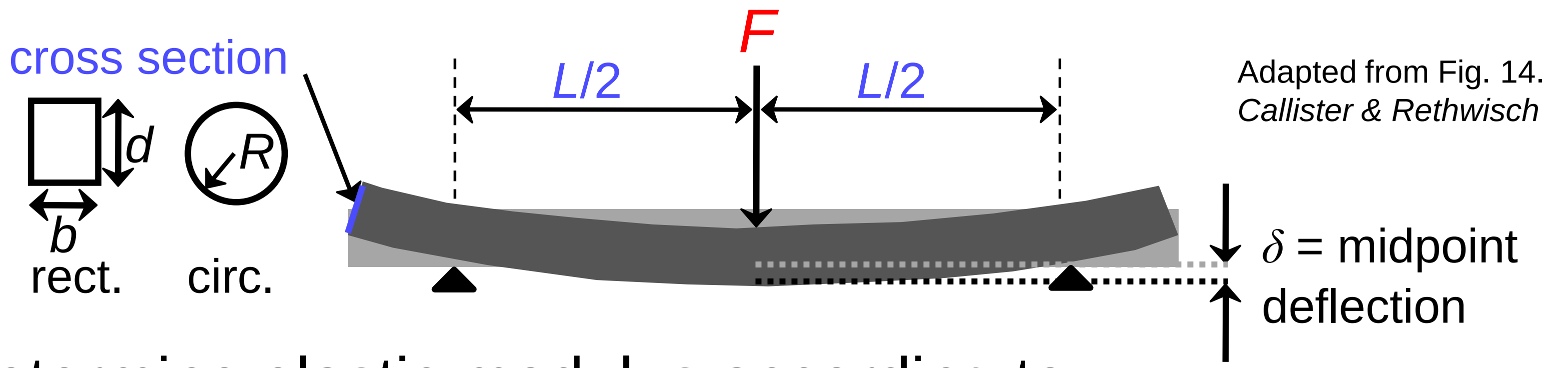
where M = maximum bending moment
c = distance from center of specimen to outer fibers
I = moment of inertia of cross section
F = applied load

	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

Flexural Tests – Measurement of Elastic Modulus

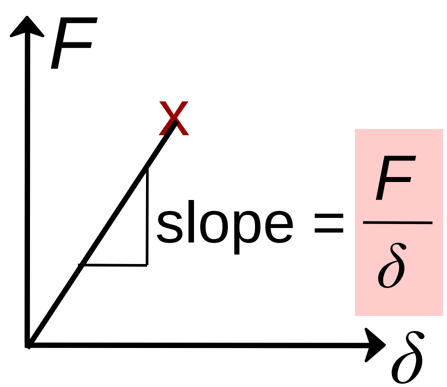
- Room *T* behavior is usually elastic, with brittle failure.
- 3-Point Bend Testing often used.

  -- tensile tests are difficult for brittle materials.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Determine elastic modulus according to:



linear-elastic behavior

$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} \quad \text{(rect. cross section)}$$

$$E = \frac{F}{\delta}\frac{L^3}{12\pi R^4} \quad \text{(circ. cross section)}$$

EXAMPLES OF QUESTION

A circular specimen of MgO is loaded using a three-point bending mode. Compute the minimum possible radius of the specimen without fracture, given that the applied load is 425 N, the flexural strength is 105 MPa, and the separation between load points is 60 mm.

A three point bending test is performed on a spinel ($MgAl_2O_4$) specimen having a rectangular cross-section of height d=3.8 mm and b=9 mm, the distance between support points is 25 mm.

(i) Estimate the flexural strength if the load at fracture is 350 N.

(ii) Compute the maximum deflection at the center of the specimen. (Young 's Modulus of spinel is 260 GPa).

APPLICATIONS

Ceramics are everywhere but there are not just pots and tableware!

The raw materials for these products are clay; traditional ceramics.

Taxonomy of Ceramics

Ceramic Materials

- **Glasses**
  - -optical
  - composite reinforce
  - containers/ household

- **Clay products**
  - -whiteware
  - bricks

- **Refractories**
  - -bricks for high *T* (furnaces)

- **Abrasives**
  - -sandpaper
  - cutting
  - polishing
- **Cements**
  - -composites
  - structural
- **Advanced ceramics**
  - engine
    - rotors
    - valves
    - bearings
  - -sensors

Glass

- Non crystalline silicates containing network modifiers; Na_2O, CaO, K_2O and Al_2O_3
- Typical example of glass; soda-lime silica glass → 70% SiO_2 + soda (Na_2O) and lime (CaO)
- Glass is transparent and easy to be fabricated

Applications of Glasses

Glass Type	Composition (wt%)						Characteristics and Applications
	SiO_2	Na_2O	CaO	Al_2O_3	B_2O_3	Other	
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (thermally shock resistant)
96% Silica (Vycor™)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex™)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda–lime)	74	16	5	1		4MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4MgO	Easily drawn into fibers—glass–resin composites
Optical flint	54	1				37PbO, $8K_2O$	High density and high index of refraction—optical lenses
Glass–ceramic (Pyroceram™)	43.5	14		30	5.5	$6.5TiO_2$, $0.5As_2O_3$	Easily fabricated; strong; resists thermal shock—ovenware

Applications of Glasses

96% Silica
Laboratory ware

Borosilicate, 81% Silica, 3.5% Na_2O, 2.5% Al_2O_3 and 3% B_2O_3
Pyrex
Laboratory ware/oven wear

Glass-Ceramics

- Most glass are amorphous (non crystalline)
- But can be transformed to crystalline by heat treatment → fine grained polycrystalline material – glass-ceramics
- The heat treatment process → devertification process
- During the heat treatment process, a nucleating agent is required to initiate crystallization or devertification process

Applications of Glass Ceramics

glassware

- **Properties/characteristics**
  - High mechanical strength
  - Low coefficient of thermal expansion
  - withstand high temperature
  - Good biological compatibility
  - Good thermal conductivity
  - Electrical insulator

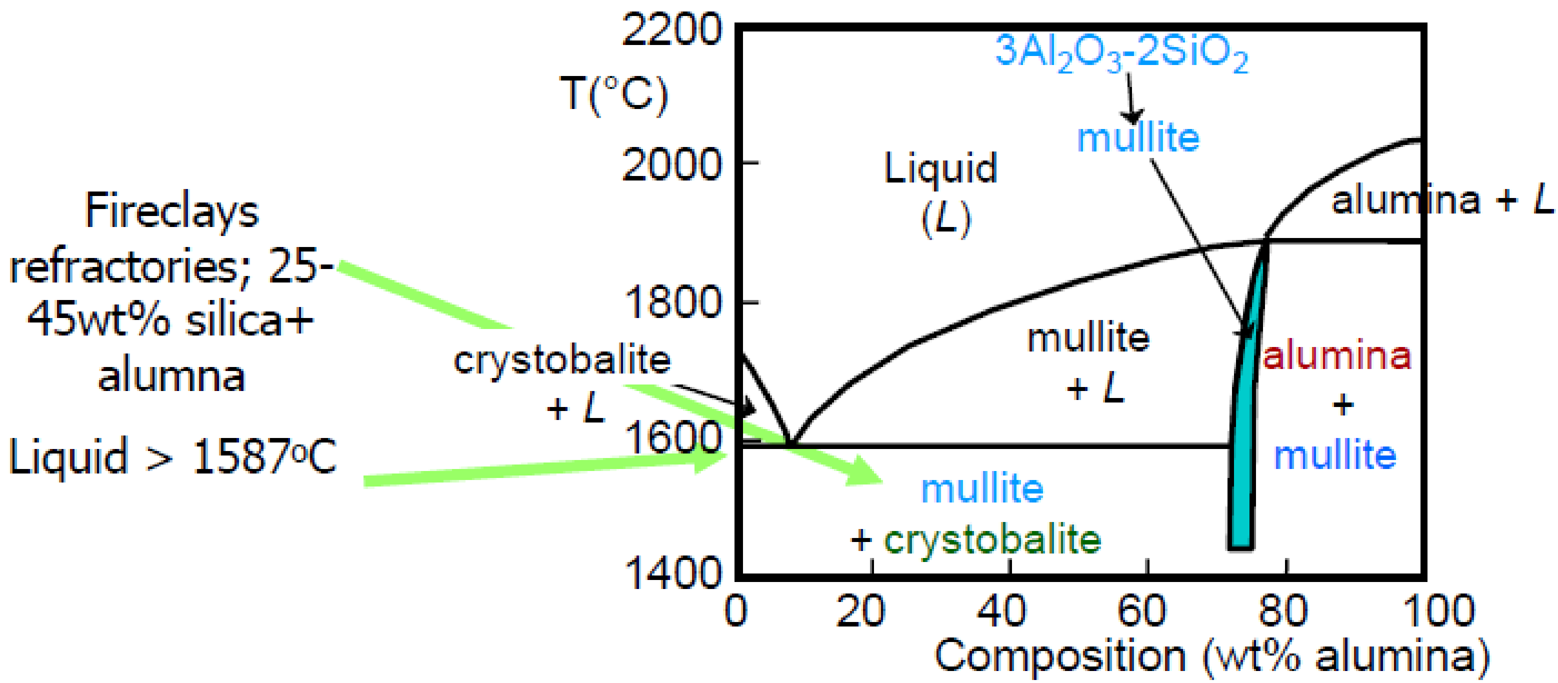
- **Other Applications**
  - Electrical insulator
  - Substrate for printed circuits board

Characteristic of Refractory Ceramics

- Can withstand high temperature without melting or decomposing
- Can remain inert even at sever conditions
- Can provide thermal insulations
- In a form of bricks
- Use as furnace linings for metal refining, glass manufacturing and power generation

Application: Refractories

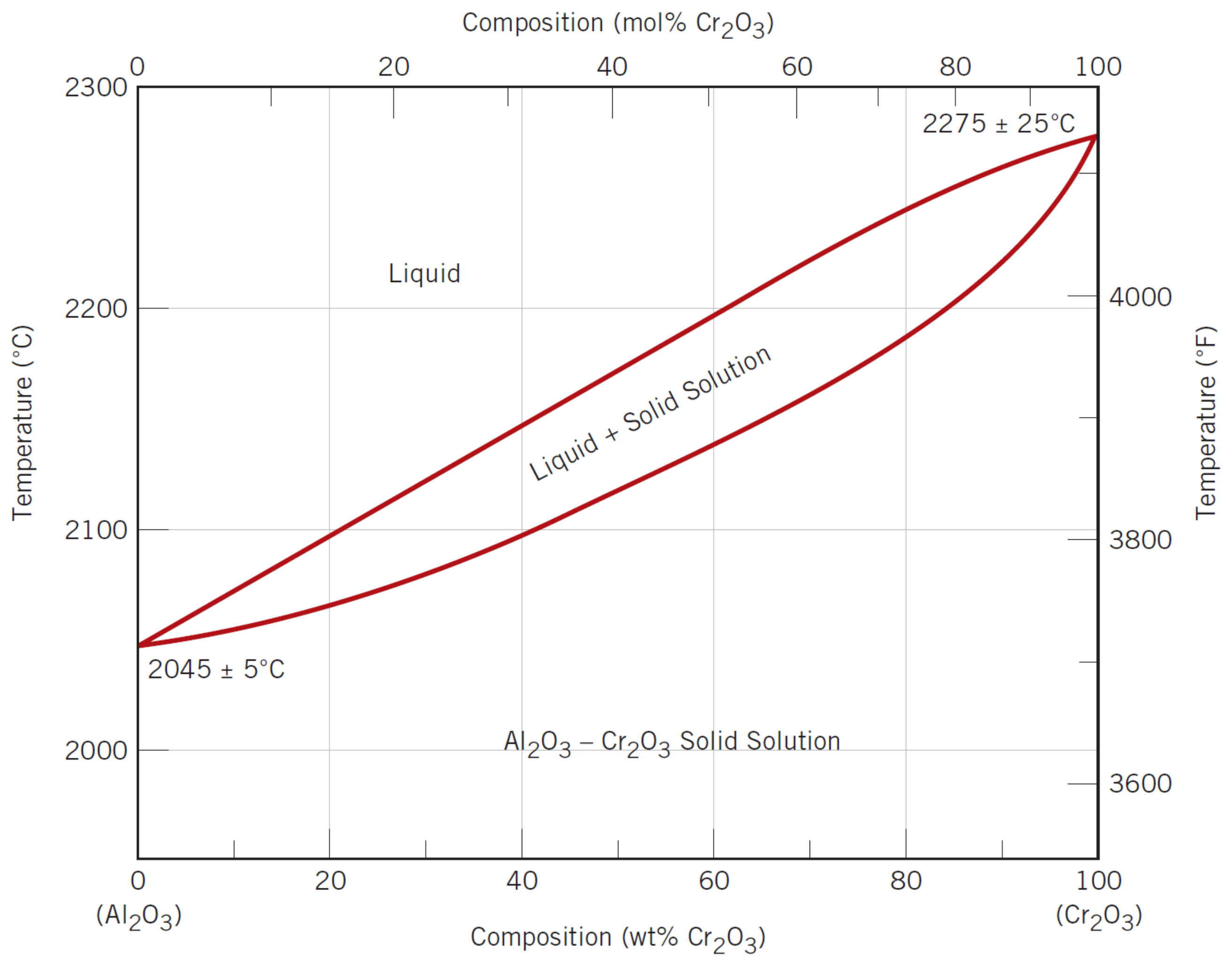
- Need a material to use in high temperature furnaces.
- Consider the Silica (SiO_2) - Alumina (Al_2O_3) system.
- Phase diagram shows:
  mullite, alumina, and crystobalite as candidate refractories.



Ceramic Phase Diagrams

Al_2O_3 -Cr_2O_3 diagram:

Figure 12.24 The aluminum oxide–chromium oxide phase diagram. (Adapted from E. N. Bunting, "Phase Equilibria in the System Cr_2O_3–Al_2O_3," *Bur. Standards J. Research*, **6,** 1931, p. 948.)



Ceramic Phase Diagrams

MgO-Al_2O_3 diagram:

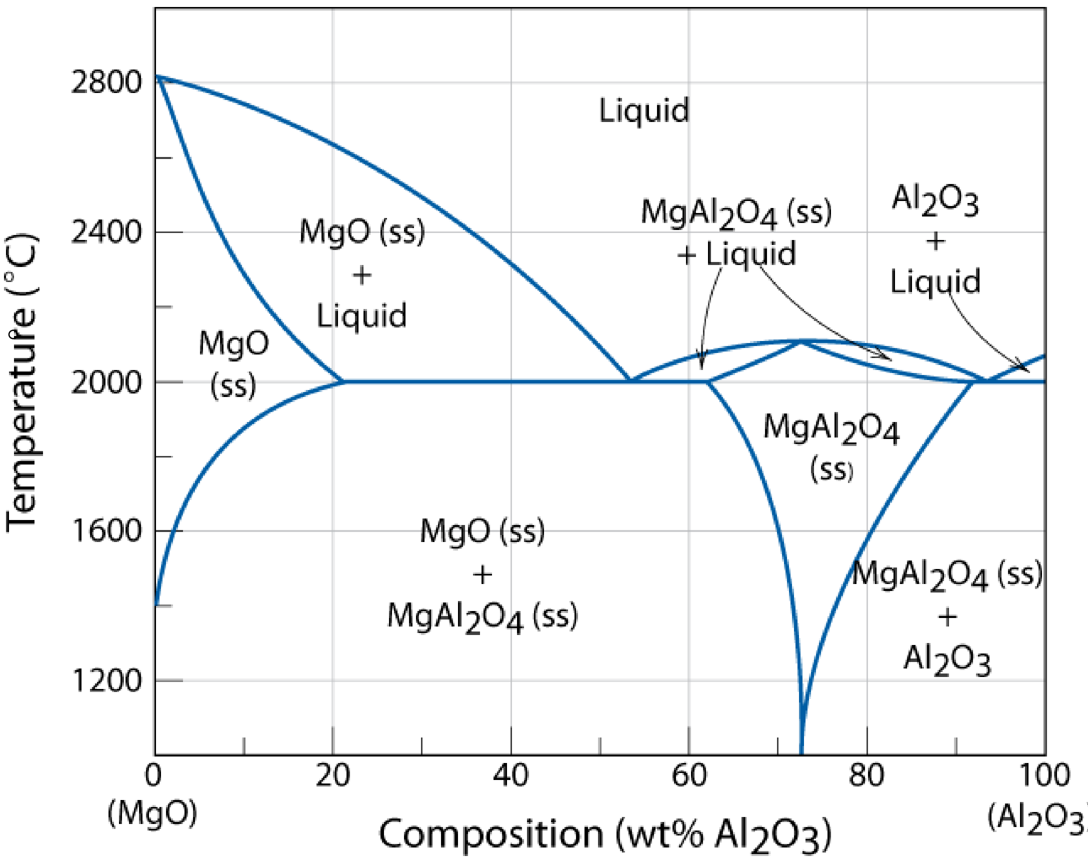


Fig. 14.2, Callister & Rethwisch 9e.
[Adapted from B. Hallstedt, "Thermodynamic Assessment of the System MgO–Al_2O_3," J. Am. Ceram. Soc., 75[6], 1502 (1992). Reprinted by permission of the American Ceramic Society.]

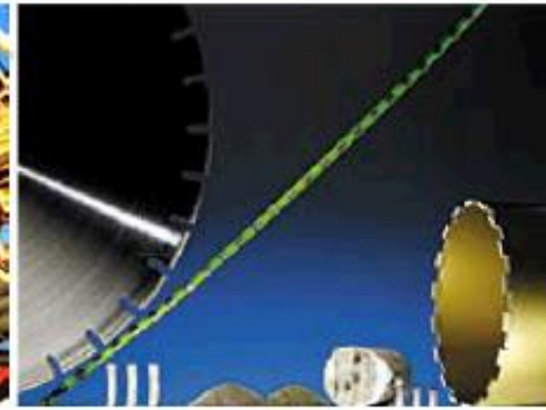
Abrasive Ceramics

- Used to wear, grind and cut away other material
- Hardness and wear resistance important
- High degree of toughness – do not want material which deform or facture during cutting!
- Diamond is the best but expensive
- Other examples; WC, Al_2O_3 and SiO_2

Application: Abrasive ceramics: Cutting Tools

- Tools:
  -- for grinding glass, tungsten, carbide, ceramics
  -- for cutting Si wafers
  -- for oil drilling


oil drill bits


blades

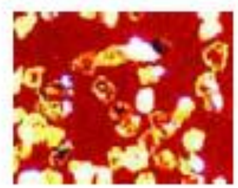
Abrasive are used in several forms:

-- manufactured single crystal or polycrystalline diamonds in a metal or resin matrix.

-- optional coatings (e.g., Ti to help diamonds bond to a Co matrix via alloying)

-- polycrystalline diamonds resharpen by microfracturing along crystalline planes.


coated single crystal diamonds

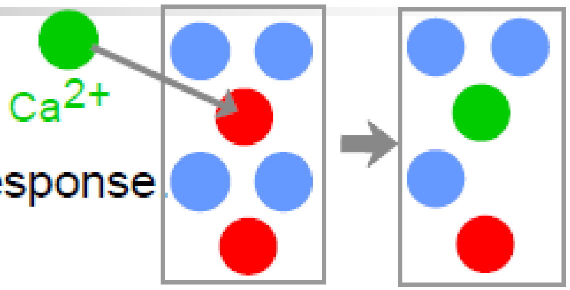

polycrystalline diamonds in a resin matrix.

Advance Ceramics

1. Ceramics that displays unique electrical, magnetic and optical properties
2. Sensors, fuel cells, superconductors, actuators, electronics packaging, semiconductor devices, solar cells, fibre optics, laser production etc etc…

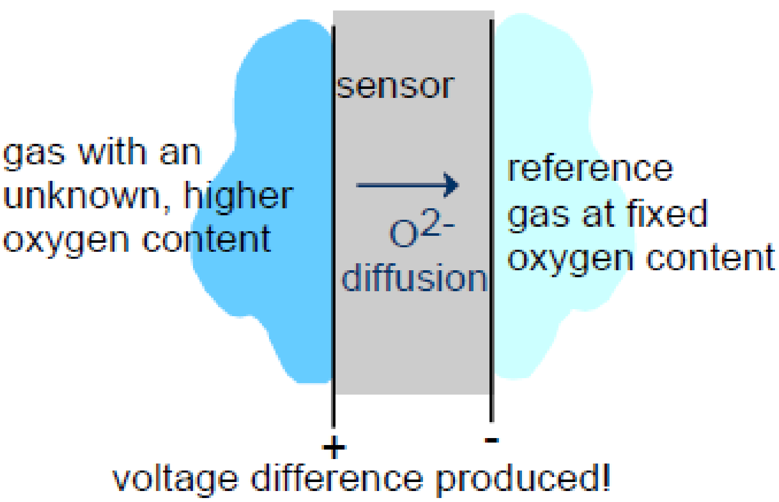
Application: Sensors

- Example: Oxygen sensor ZrO_2
- Principle: Make diffusion of ions fast for rapid response.
- Approach:
  Add Ca impurity to ZrO_2:
  -- increases O^{2-} vacancies
  -- increases O^{2-} diffusion rate



A Ca^{2+} impurity removes a Zr^{4+} and a O^{2-} ion.

- Operation:
  -- voltage difference produced when O^{2-} ions diffuse from the external surface of the sensor to the reference gas.



Applications: Advanced Ceramics

Heat Engines

- Advantages:
  - Run at higher temperature
  - Excellent wear & corrosion resistance
  - Low frictional losses
  - Ability to operate without a cooling system
  - Low density

- Disadvantages:
  - Brittle
  - Too easy to have voids- weaken the engine
  - Difficult to machine

- Possible parts – engine block, piston coatings, jet engines

Ex: Si_3N_4, SiC, & ZrO_2

Applications: Advanced Ceramics

- Ceramic Armor
  - Al_2O_3, B_4C, SiC & TiB_2
  - Extremely hard materials
    - shatter the incoming bullet
    - energy absorbent material underneath

Applications: Advanced Ceramics

Electronic Packaging

- Chosen to securely hold microelectronics & provide heat transfer
- Must match the thermal expansion coefficient of the microelectronic chip & the electronic packaging material. Additional requirements include:
  - good heat transfer coefficient
  - poor electrical conductivity
- Materials currently used include:
    - Boron nitride (BN)
    - Silicon Carbide (SiC)
    - Aluminum nitride (AlN)
      - thermal conductivity 10x that for Alumina
      - good expansion match with Si