

## Lecture 9

### EFFECTS OF MICROSTRUCTURE ON PROPERTIES

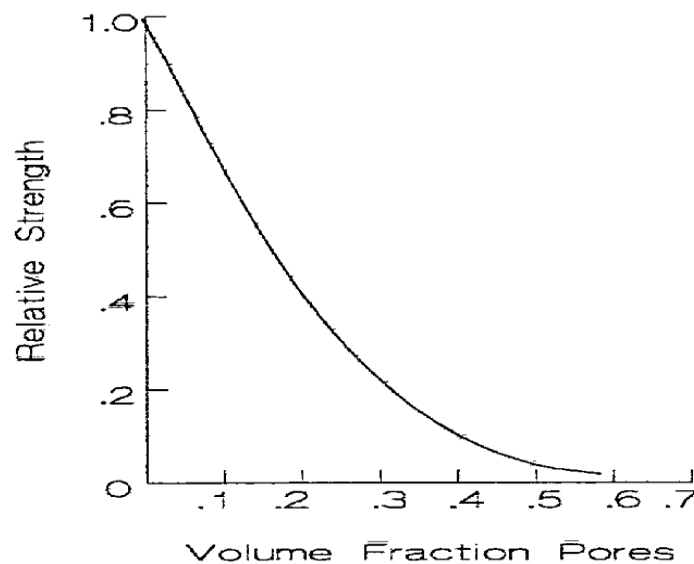
This lecture examines the impact of microstructure on the mechanical and physical properties of materials. Microstructure, which includes grain size, phase, and impurity distribution, determines a material's strength, ductility, hardness, and corrosion resistance. Manufacturing processes and heat treatment alter this structure to enhance material performance.

**The concept of microstructure:** It is the internal structure of matter that is not visible to the naked eye, such as the distribution of grains and phase.

#### Porosity/Properties

##### *Strength*

As expected, strength decreases as the volume fraction of pores increases. This is shown in Figure 1

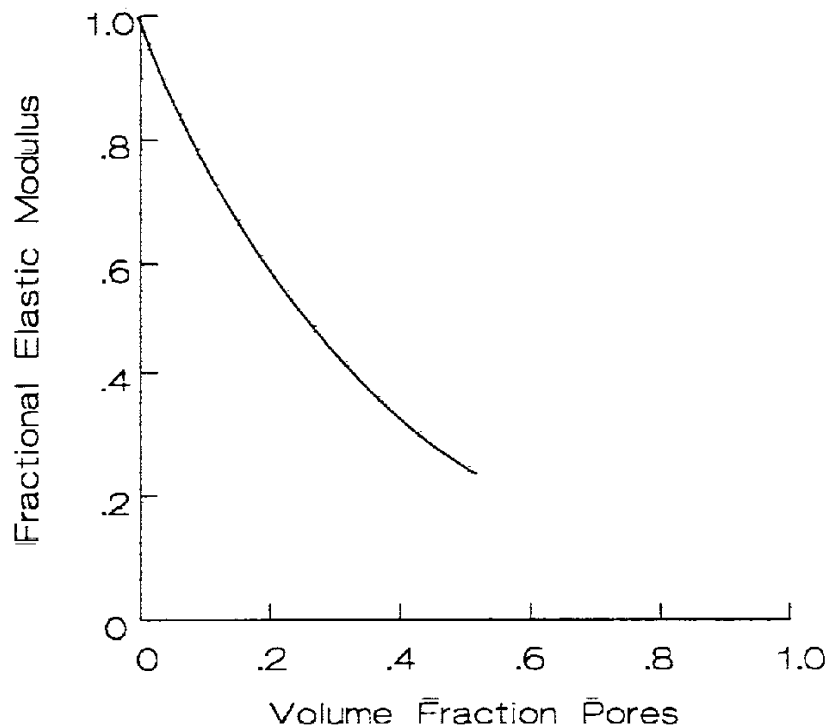


**Figure 1:** Strength with Volume Fraction Porosity. Strength drops rapidly as the porosity increases.

The curve applies to a variety of materials. For most ceramics, the part will not hold together when the volume fraction of pores exceeds about 40-50% for a normal microstructure.

### *Elastic modulus*

The elastic modulus follows a similar relationship as strength, with the modulus decreasing as the pore volume increases. This is shown in Figure 2.



**Figure 2:** MOE with Volume Fraction Porosity. The modulus of elasticity also drops off rapidly as porosity increases.

Thermal shock resistance increases with an increase in percentage pore volume due to the lower modulus.

## Grain Size

Grain size (measured as the intercept on a polished surface) affects the physical properties of strength, fracture toughness, and hardness.

### Strength

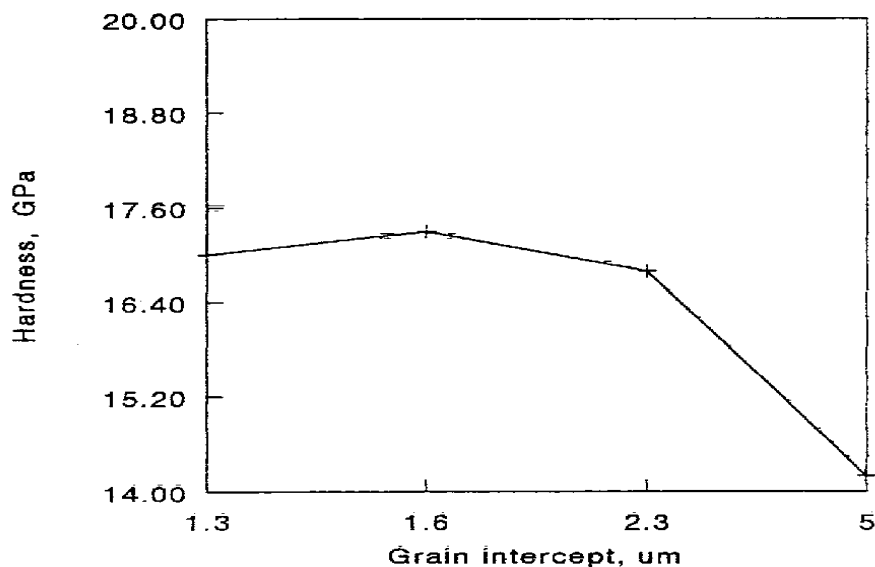
Over-firing a ceramic substantially decreases the MOR. A 100 °C increase in the soak temperature decreases the strength from 632 MPa to 337 MPa while increasing the grain intercept from 1.4 mm to 4.8 mm.

### Fracture toughness

Fracture toughness increases as the grains grow larger.

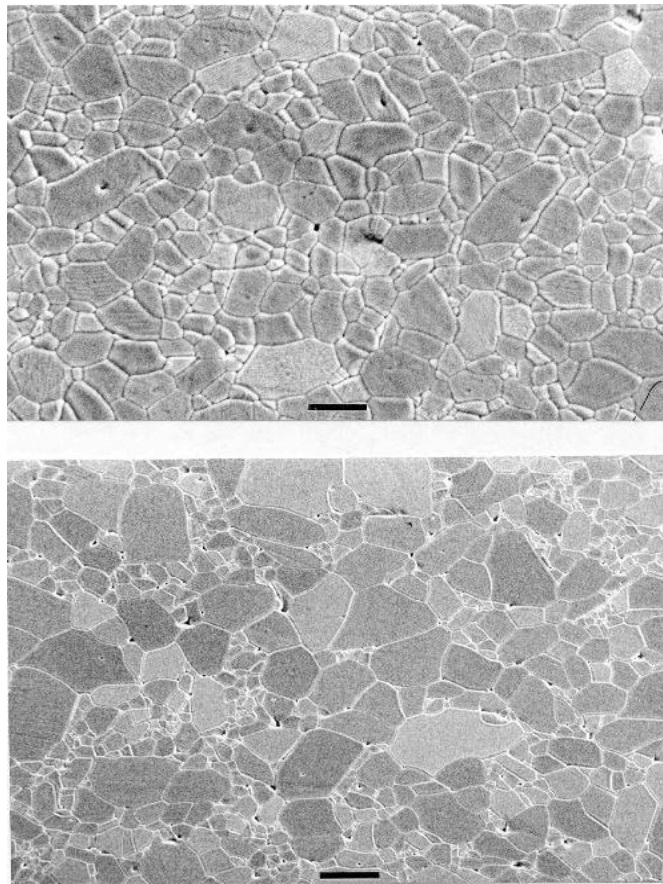
### Hardness

Figure 3 shows the relation between Vickers hardness and grain intercept. Hardness is flat until the microstructure begins to show exaggerated grain growth. The drop is fairly large.



**Figure 3.** Vickers Hardness with Grain Intercept. Hardness drops off as the grain size increases

Grain growth is flat up to 1550 °C and then starts to increase. The temperature rises of 50 °C to 1650 °C results in substantial growth. For most applications, this ceramic is over-fired. The microstructures of the 1550 and 1650 °C materials are shown in Figure 4. Note that there is a fivefold increase in magnification between the two photographs in Figure 4. Both photos are essentially fully dense. Measurements on grain intercept were made on these photos and two others at the other sintering temperature. Evidence of exaggerated grain growth is seen in the 1650 °C firing temperature photo.



**Figure 4:** Microstructure Alumina Fired at 1550-1650 °C. Note the change in magnification between the two figures. Scale bar 10  $\mu\text{m}$  on both.

## ***Wear Resistance***

Wear resistance is one of the most important properties of ceramic materials, making them superior to metals in demanding applications. In ceramics, wear is not caused by simple scratching, but is entirely controlled by the microstructure.

## ***Factors Affecting Corrosion Resistance***

**Hardness:** The harder a material is, the greater its corrosion resistance. Ceramics (such as carbides and oxides) possess strong covalent bonds that prevent surface deformation.

**Grain Size:** Fine-grained ceramics offer significantly better corrosion resistance because their large grain boundary area inhibits surface crack propagation.

Alumina: Excellent in dry abrasive corrosion, but may suffer from grain fragmentation if porosity is high.

Zirconia (TZP): The "queen" in wet friction applications and industrial joints due to its exceptional softness and durability, which prevents surface fracture.

Silicon Carbide (SiC): Used in mechanical seals for its outstanding corrosion resistance in harsh chemical environments.

## ***Phase Composition***

The phase composition in ceramics refers to the nature and types of “phases” (crystalline or glassy forms) that make up the material, and it determines the final identity of the mechanical and thermal properties.

### **1. Phase Types in Ceramics**

Ceramics are not always composed of a single type of crystal, but are often a mixture of:

**Crystalline Phase:** Atoms arranged in a precise geometric pattern, responsible for high hardness.

**Glassy/Amorphous Phase:** A disordered material often found at the grain boundaries. It acts as a binder but weakens the material at high temperatures because it softens quickly.

### **2. The Effect of Phase Composition on Properties**

**Toughness:** In TZP ceramics, the phase composition is key to its strength; The tetragonal phase is maintained at room temperature. Without this specific composition, zirconia loses its crack resistance.

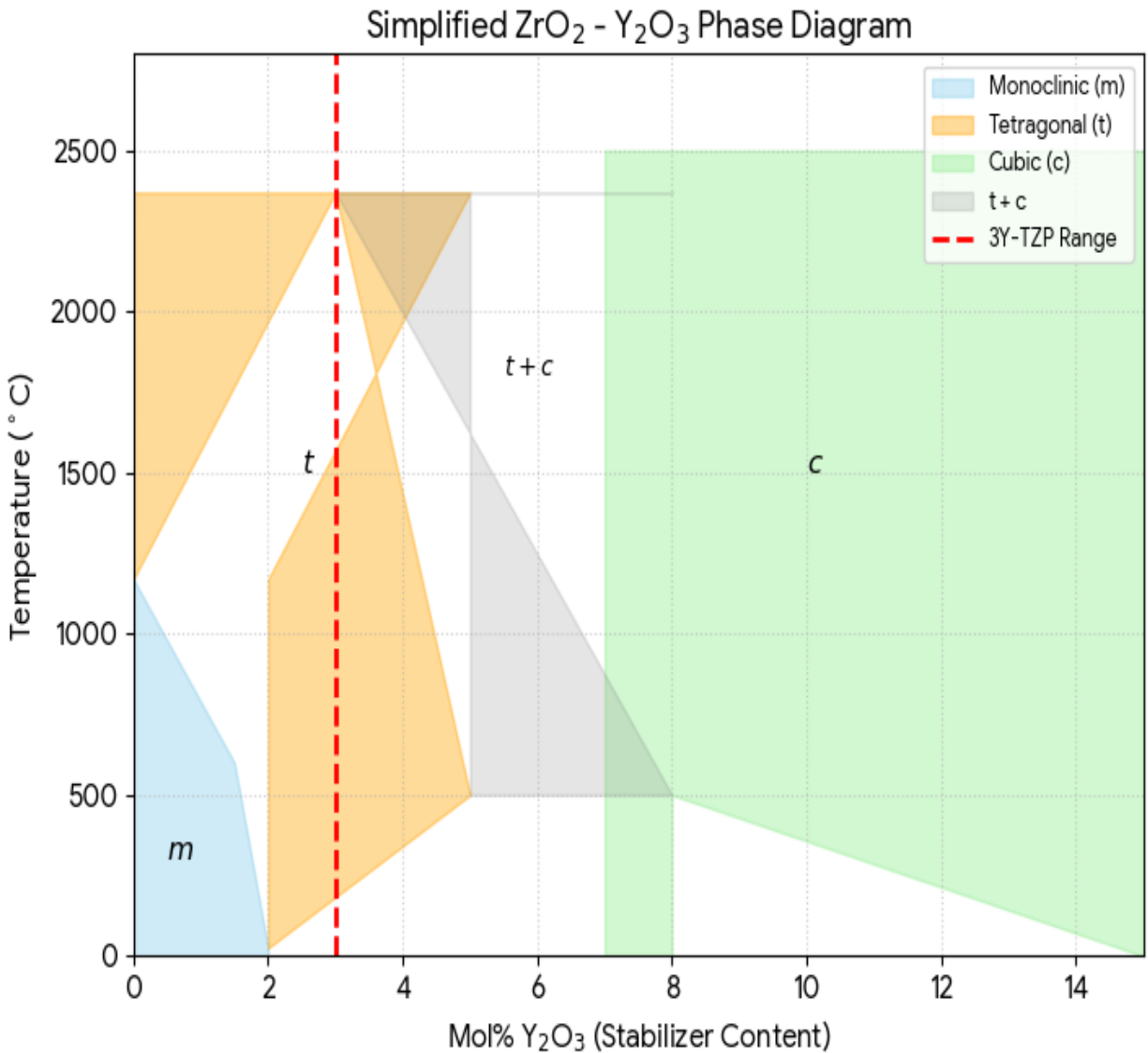
### **3. Phase Control**

**Phase composition is manipulated through:**

**Additives (Dopants):** such as adding magnesia or yttria to stabilize certain phases.

**Heat Treatment:** The cooling or heating rate determines which phases will form and which will remain metastable.

**Pressure:** As mentioned in the TZP example, mechanical pressure can alter the phase composition from one phase to another (strain-induced transformation).



**Figure 5.** The diagram shows the "phase map" of zirconia ceramics when yttria ( $Y_2O_3$ ) is added as a stabilizer.

Here is an analysis of the diagram and its relation to the material's properties:

### 1. The three main phases:

***Monoclinic phase (m)***: Shown in the blue area (left). This is the stable phase at room temperature for pure zirconia, but it is mechanically weak due to the large size of its crystal cells.

***Tetragonal phase (t)***: Shown in the orange area. This is the "heart" of TZP ceramic strength. By adding approximately 3% yttria (dashed red line), we can maintain this strong phase in a "semi-stable" state even at room temperature.

***Cubic phase (c)***: Shown in the green area (right). This is the most thermally stable phase and is used in cubic zirconia (jewelry) or high-temperature insulators.

### 2. Significance of the Red Line (TZP Region):

At a concentration of 3 mol% yttria, we find a region where the ceramic is composed almost entirely of very fine tetrahedral grains.

**Property Prediction:** In this region, we expect the highest fracture toughness values due to the ability of these grains to instantly revert to the monoclinic phase when subjected to fracture compression, thus sealing the fracture.

### **3. Mixed Regions (t + c):**

In these regions, grains from both phases coexist. This type is known as "Partially Stabilized Zirconia" (PSZ), and it offers a balance between thermal resistance and mechanical toughness.