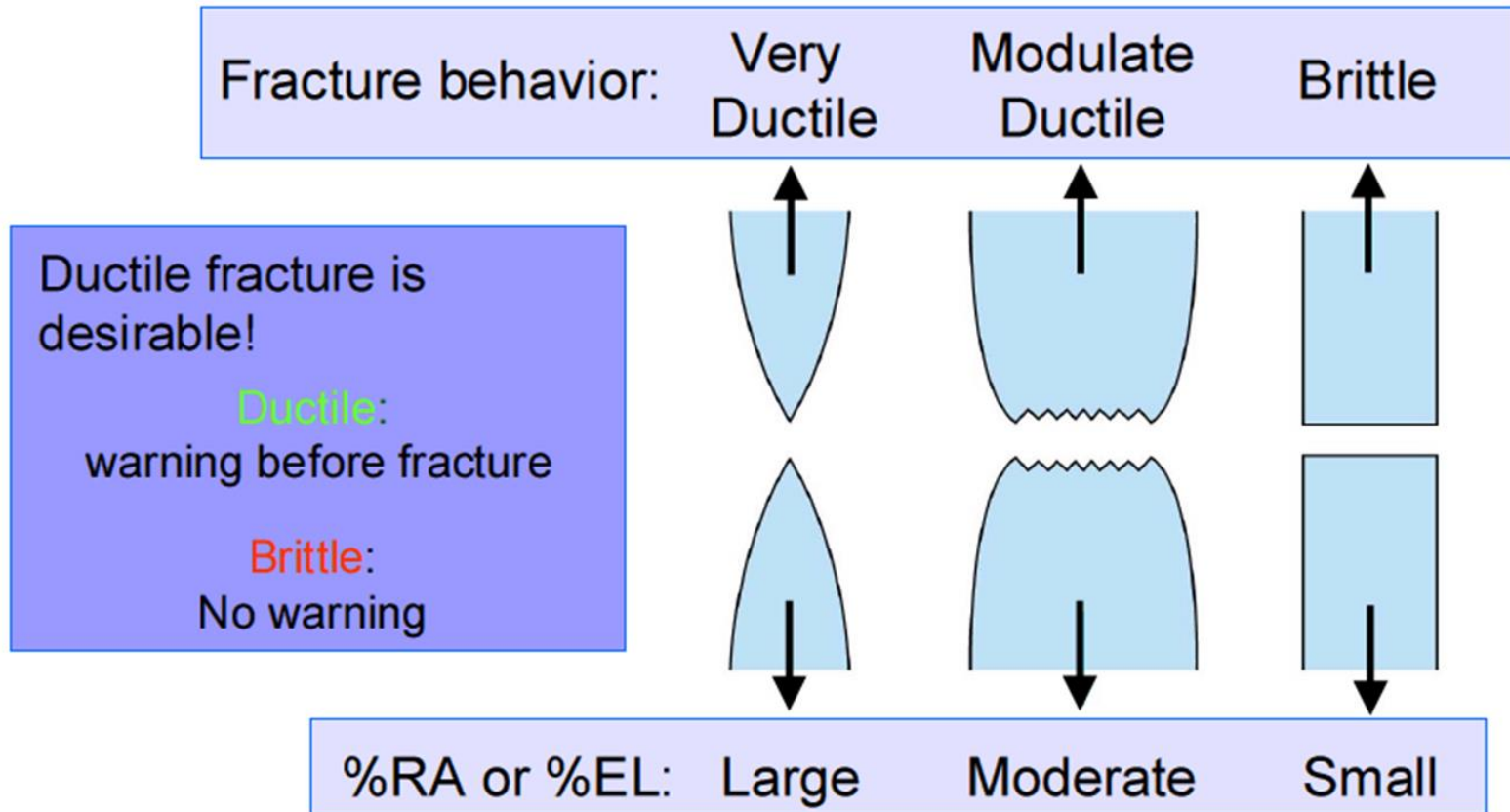


Composite Materials

Ceramic Matrix Composites

Ductile vs. Brittle Fracture

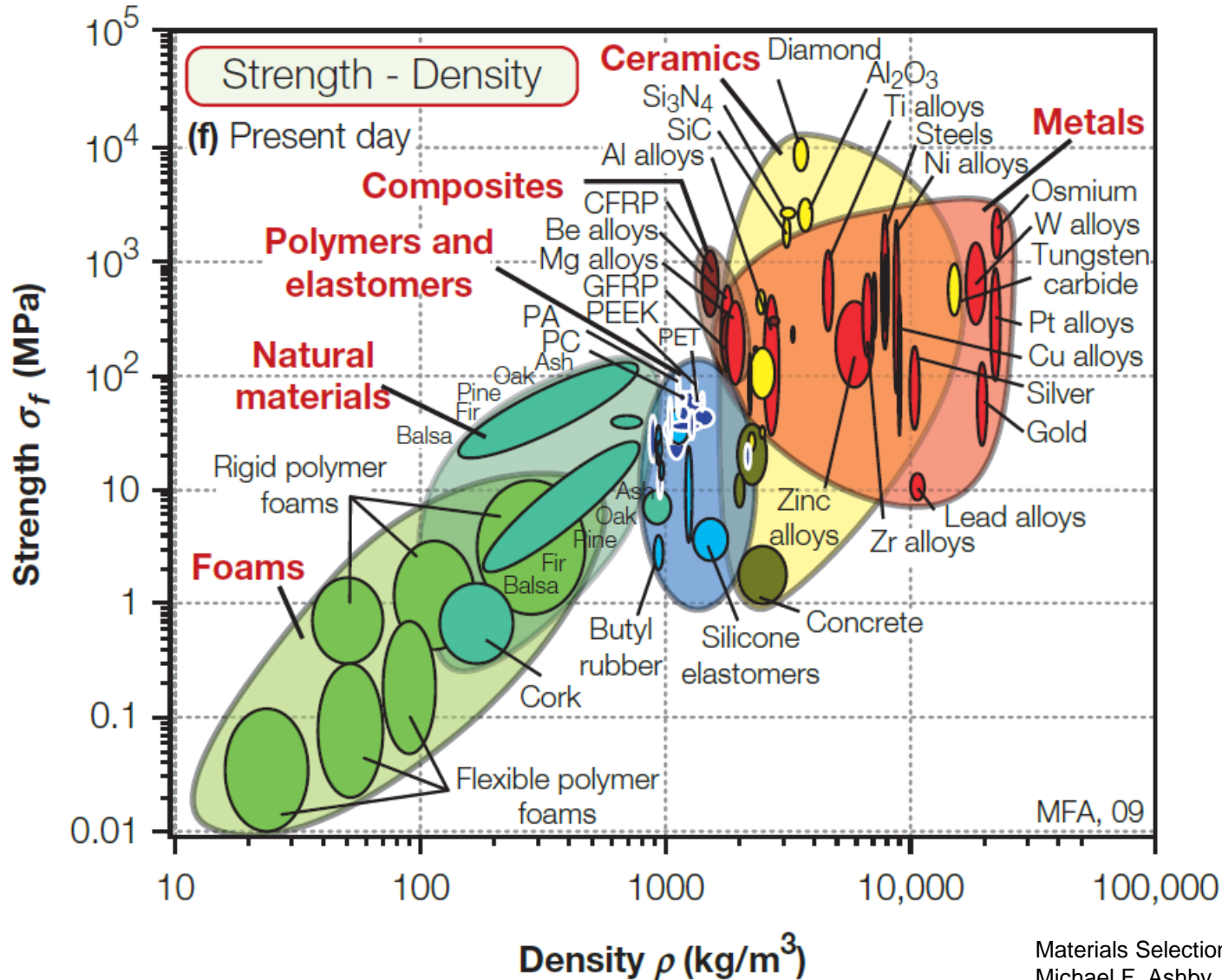


Ceramic materials → brittle fracture !!!

General Properties of Ceramics

- High stiffness
- High compressive strength
- High hardness
- Wear resistance
- Brittle fracture
- Low tolerance for stress concentrations or contact stresses
- Wide scatter in mechanical properties due to porosity

Introduction



Properties of Some Ceramic and Selected Nonceramic Materials

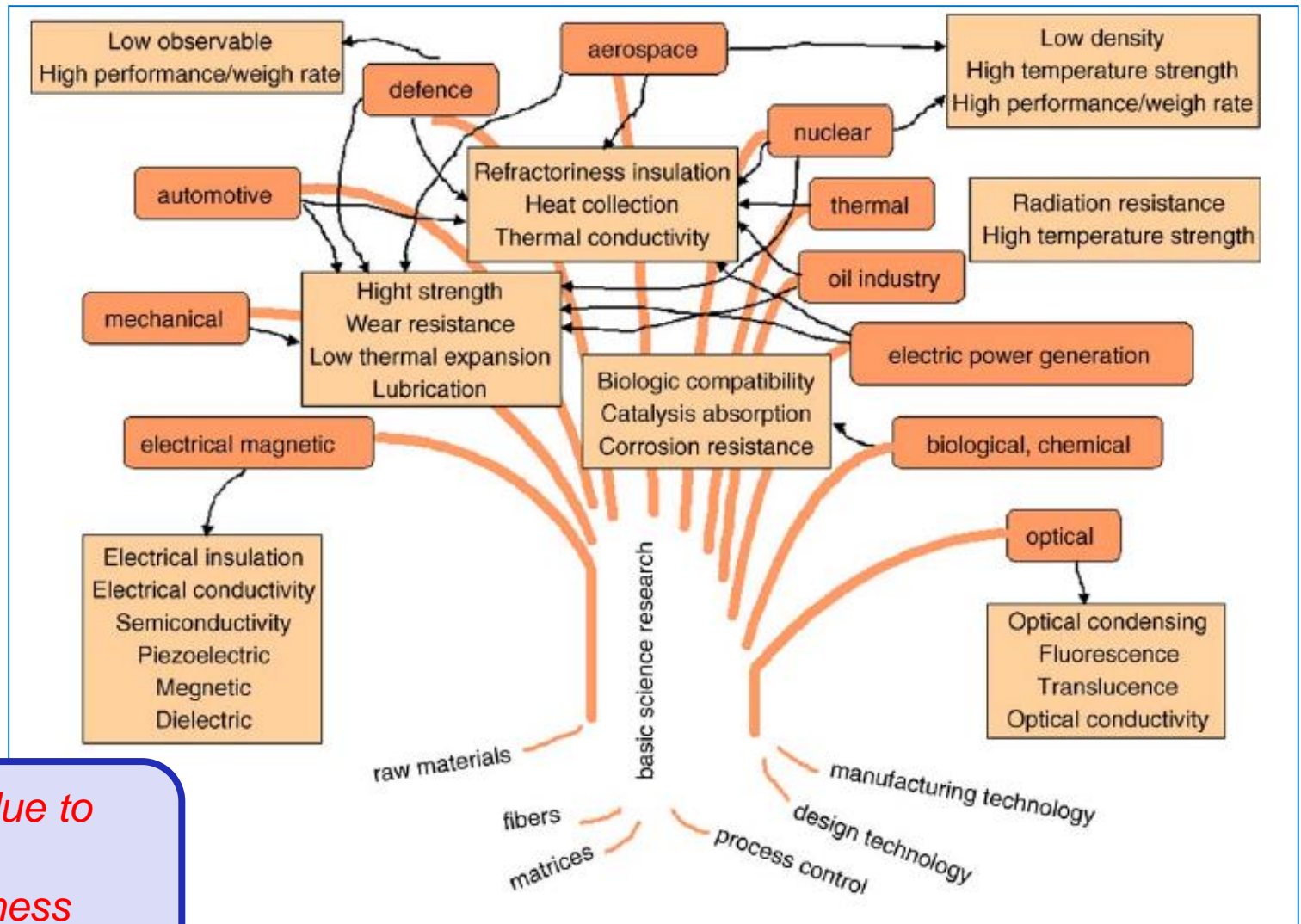
Material	Melting Point (°C)	Density (g/cm ³)	Hardness (Mohs) ^a	Modulus of Elasticity ^b	Coefficient of Thermal Expansion ^c
Alumina, Al ₂ O ₃	2050	3.8	9	34	8.1
Silicon carbide, SiC	2800	3.2	9	65	4.3
Zirconia, ZrO ₂	2660	5.6	8	24	6.6
Beryllia, BeO	2550	3.0	9	40	10.4
Mild steel	1370	7.9	5	17	15
Aluminum	660	2.7	3	7	24

^aThe Mohs scale is a logarithmic scale based on the relative ability of a material to scratch another softer material. Diamond, the hardest material, is assigned a value of 10.

^bA measure of the stiffness of a material when subjected to a load (MPa × 10⁴). The larger the number, the stiffer the material.

^cIn units of (K⁻¹ × 10⁻⁶). The larger the number, the greater the size change upon heating or cooling.

Advanced Ceramics Application Tree



Limitations due to

- High cost
- Low toughness
- Low reliability

Application areas of CMCs

Ceramic matrix composites (CMCs) have been developed to overcome the intrinsic **brittleness** and **lack of reliability** of monolithic ceramics, with the aim to apply ceramics in structural parts used in severe environments, such as rocket and jet engines, gas turbines for power plants, heat shields for space vehicles, fusion reactor first wall, aircraft brakes, heat treatment furnaces, etc.

Further advantages include **weight reductions** and **higher operating temperatures** compared to metals and metal matrix composites

Motivation for CMCs

Strength of ceramics depends on pore size, pore volume, grain size, and intrinsic fracture toughness of the material

General approaches for improving the fracture toughness are reducing the pore size, pore volume, grain size and increasing the toughening mechanisms

Well dispersed reinforcements in the following forms are used to increase the toughness of the ceramic matrix:

Particles

Whiskers – microfibers with exceptional mechanical properties

Chopped fibres

Continuous fibres - much more efficient in toughening the matrix

Yarns and mats

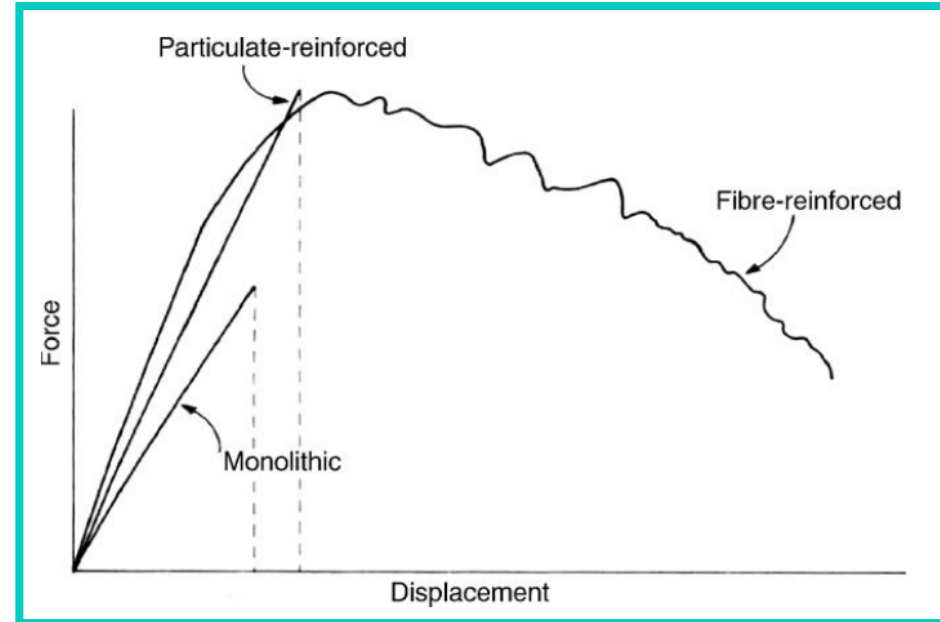
Increase in fracture toughness up to approx. $10 \text{ MPa}\cdot\text{m}^{1/2}$ (maximally up to approx. $20 \text{ MPa}\cdot\text{m}^{1/2}$ in composites with continuous fibers).

Ceramic Matrix Composites

Monolithic ceramics have reasonably high strength and stiffness but are brittle. Thus one of the main objectives in producing ceramic matrix composites is to increase the toughness.

There is also a concomitant rise in strength and stiffness.

The area under the stress–strain curve is the energy of fracture of the sample and is a measure of the toughness. It is clear from the figure that the reinforcement with particulates and continuous fibres has led to an increase in toughness but that the increase is more significant for the latter.



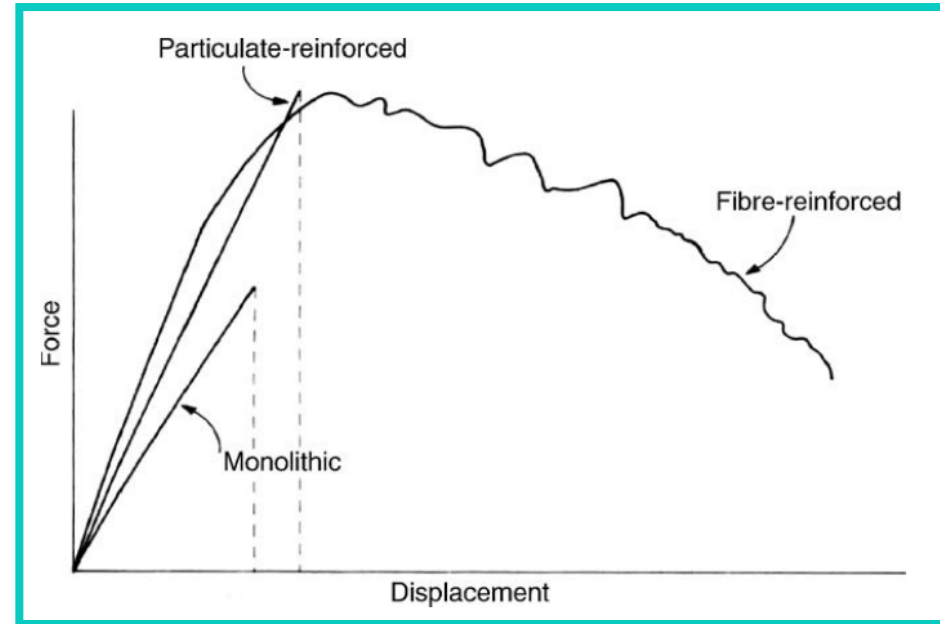
Schematic force–displacement curves for a monolithic ceramic and CMCs illustrating the greater energy of fracture of the CMCs

Ceramic Matrix Composites

Both the monolithic and the particulate-reinforced composite fail in a catastrophic manner, which contrast with the failure of the continuous fibre composite where a substantial load carrying capacity is maintained after failure has started.

Therefore not only has the continuous fibre composite a better toughness **but the failure mode is more desirable.**

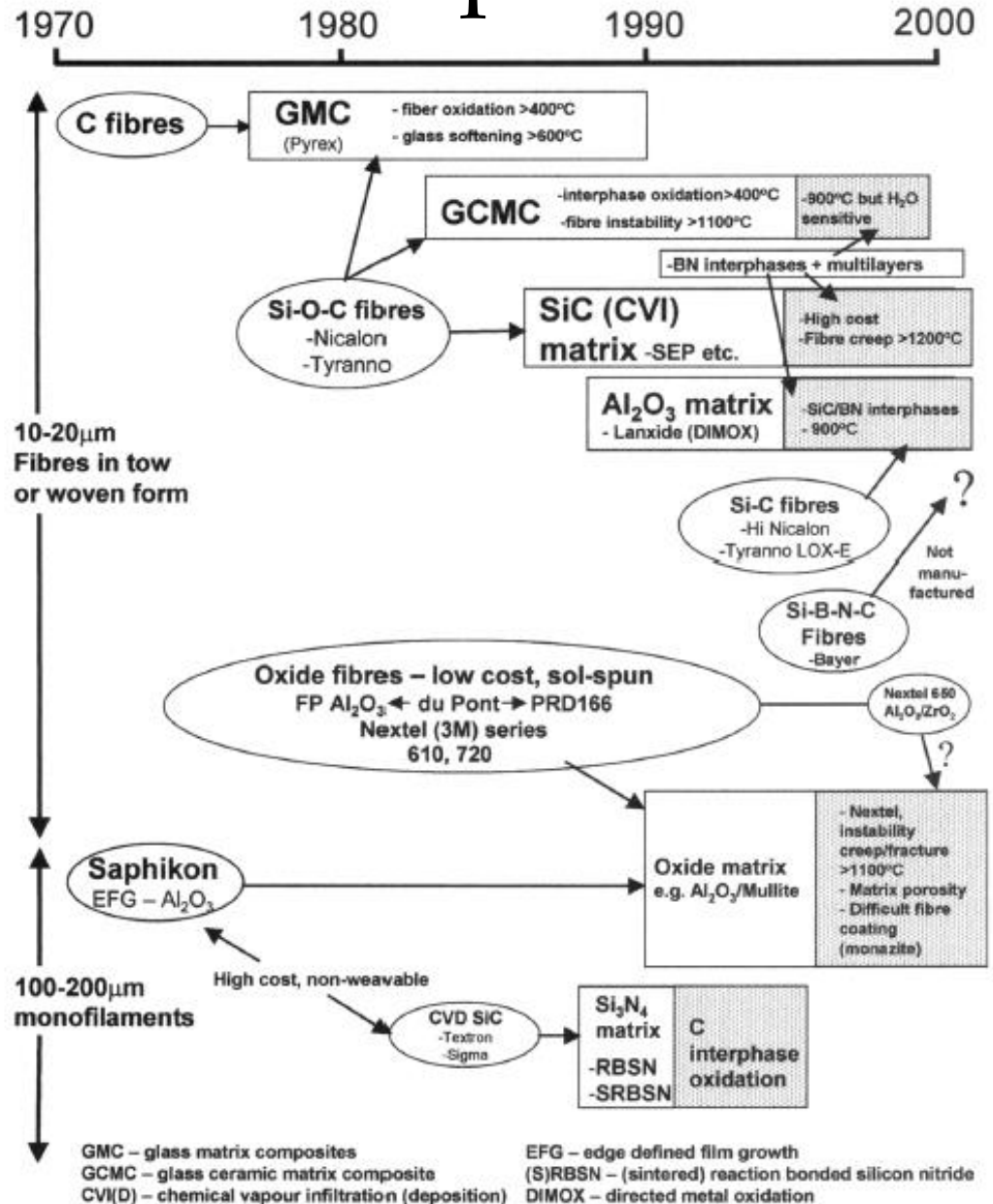
However, fibres are more expensive reinforcements than particles and the processing is more complex, therefore the improvement in toughness is associated with an extra cost burden.



Schematic force–displacement curves for a monolithic ceramic and CMCs illustrating the greater energy of fracture of the CMCs

Ceramic Matrix Composites

The historical evolution of fibres and ceramic matrix composites, indicating some of the limits to performance or commercial development.



Ceramic Matrix Composites

Ceramic matrix composites may be classified into two categories:

One is a group of **toughened ceramics reinforced with particulates and whiskers**. These materials exhibit brittle behavior in spite of considerable improvements in fracture toughness and strength. The maximum in fracture toughness is around $10 \text{ MPam}^{1/2}$ or more.

The second consists of **continuous-fiber composites** exhibiting quasi-ductile fracture behavior accompanied by extensive fiber pull out. The fracture toughness of this class of materials can be higher than $20 \text{ MPam}^{1/2}$ when produced with weak interfaces between the fibers and matrix.

Ceramic Matrix Composites

The best toughening effect is provided by dispersed phase in the form of continuous monofilament SiC fibers, which are fabricated by chemical vapor deposition (CVD) of silicon carbide on a substrate made of tungsten (W) or carbon (C) fibers.

Monofilament fibers produce stronger interfacial bonding with the matrix material improving its toughness.

Failure of long-fiber ceramic matrix composites is not catastrophic.

Typical Properties of Long-Fiber Ceramic Matrix Composites

- High mechanical strength even at high temperatures;
- High thermal shock resistance;
- High stiffness;
- High toughness;
- High thermal stability;
- Low density;
- High corrosion resistance even at high temperatures.

Toughening Mechanisms

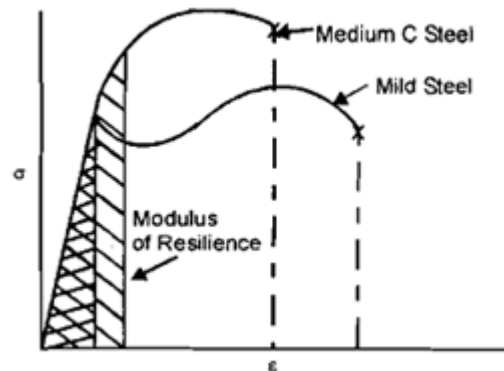
A variety of ceramic particulates, whiskers (high-strength single crystals with length/diameter ratios of 10 or more), and fibers may be added to the host matrix material to generate a composite with improved fracture toughness.

The presence of these reinforcements appears to disturb the propagation of cracks by at least three mechanisms:

- 1.** When the crack tip encounters a particle or fiber that it cannot easily break or get around, it is deflected off in another direction. Thus, the crack is prevented from propagating cleanly through the structure.
- 2.** If the bond between the reinforcement and the matrix is not too strong, crack propagation energy can be absorbed by pullout of the fiber from its original location.
- 3.** Fibers can bridge a crack, holding the two faces together, and thus prevent further propagation.

Toughening mechanisms

The area under the stress-strain curve gives us toughness



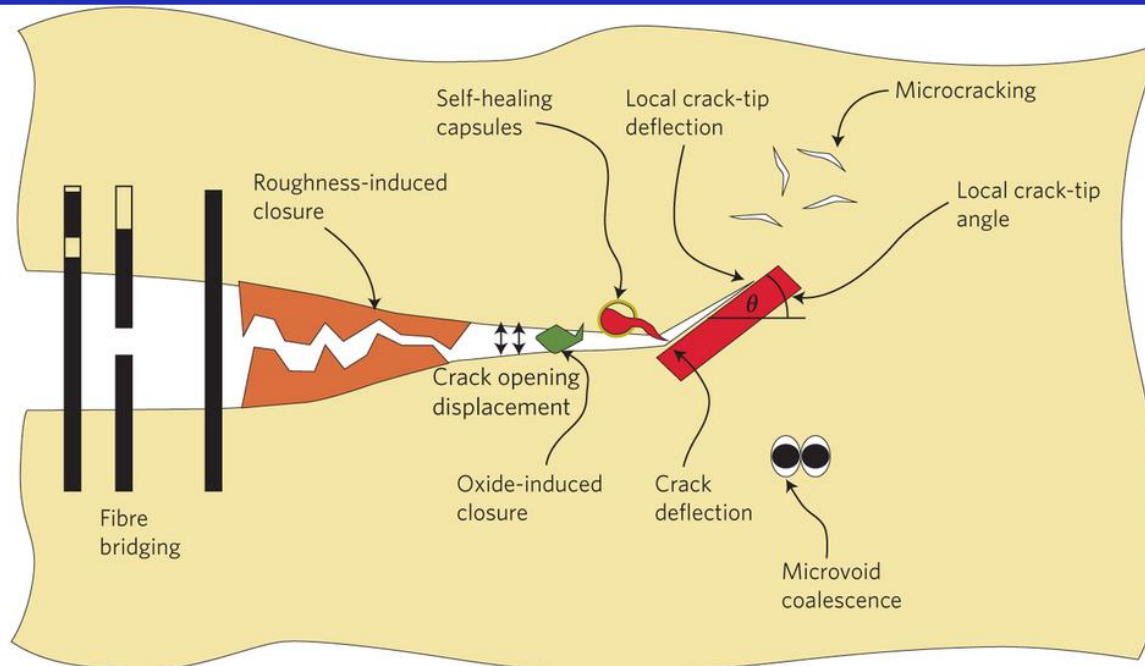
If both areas are the same, the one with the higher strength is tougher to fracture

Energy absorbing mechanisms increase toughness

When stress is applied, cracks propagate. In order to toughen the material, the crack propagation rate should decrease (slow in metals, fast in ceramics)

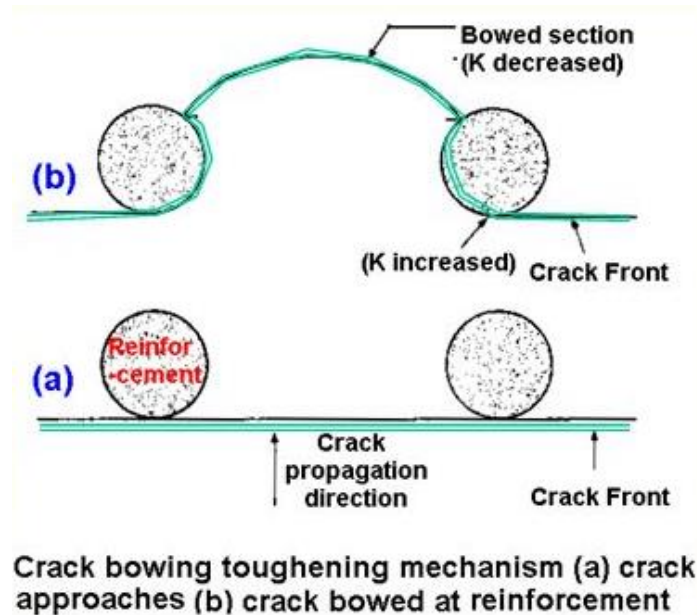
Toughening mechanisms in ceramic-matrix composites

- Crack bowing and deflection
- Crack bridging and fiber pullout
- Micro-cracking
- Transformation toughening



Toughening mechanisms

Crack bowing



Fibers result in non-linear crack front

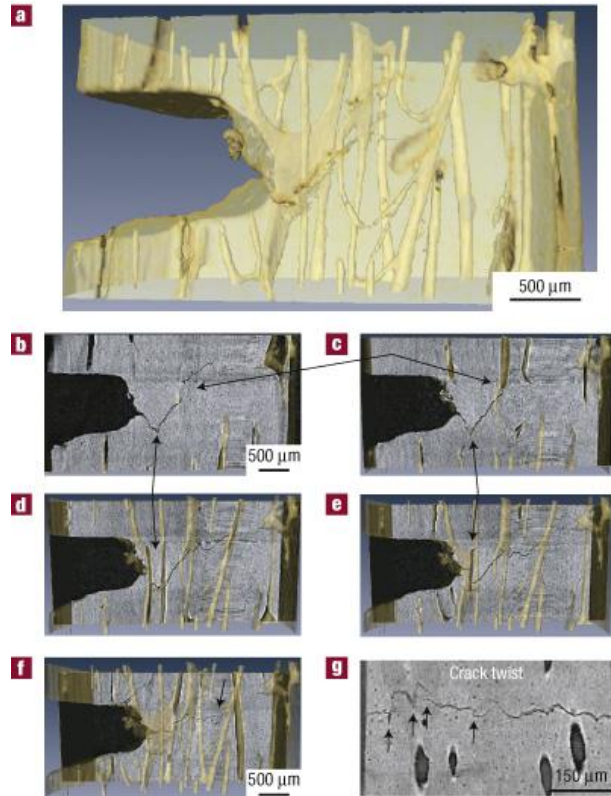
Toughness increases with fiber volume fraction and aspect ratio

The crack will move around the fiber until stress intensity factor increases at high loads and the fiber fractures

Toughening mechanisms

Crack deflection

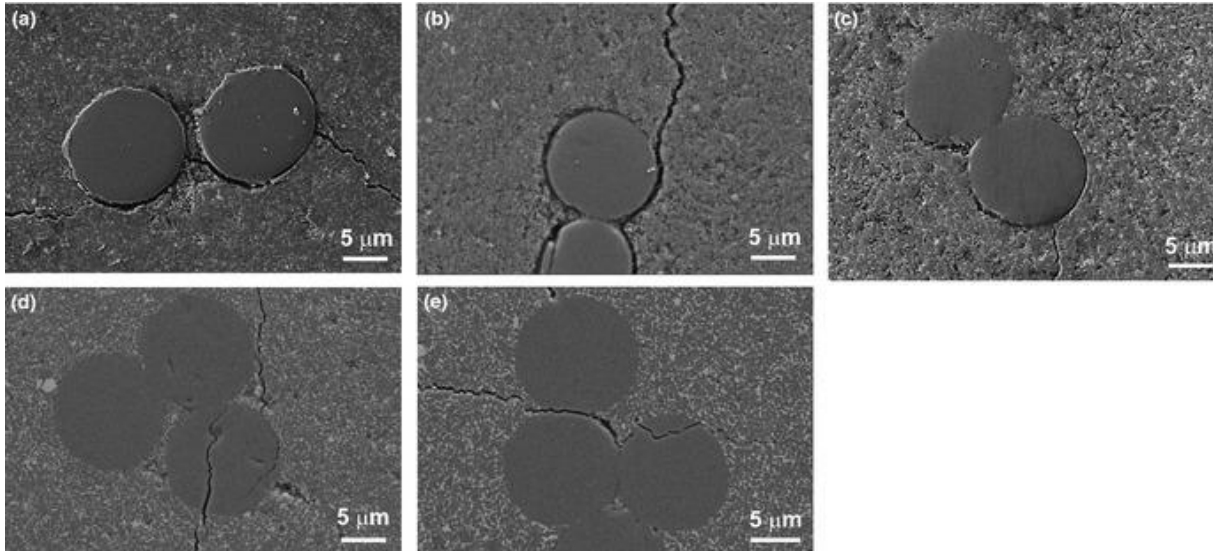
Cracks are deflected from growth plane around fibers due to differences in thermal expansion coefficient and modulus between the fiber and the matrix



Similar mechanism to crack bowing but more effective

Toughening mechanisms

Debonding



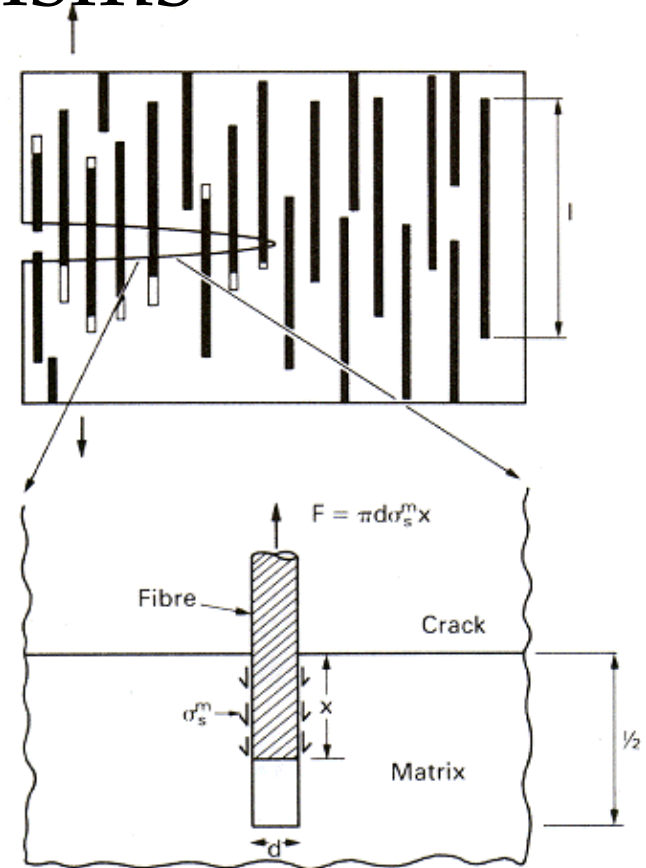
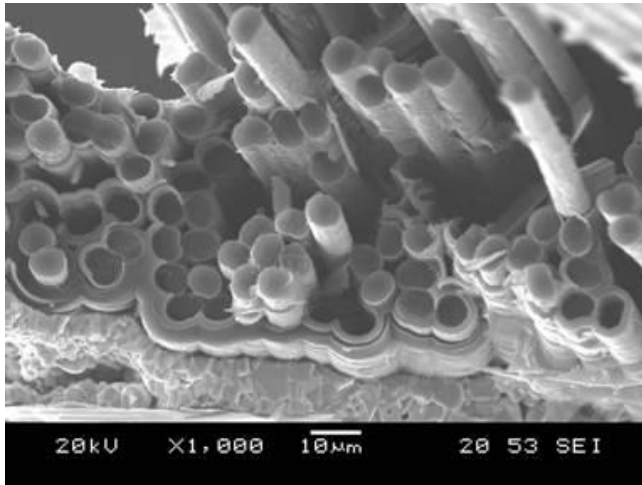
Cracks induce creation of new surfaces between the fiber and matrix

The energy needed to create the surfaces is supplied by the crack and its propagation rate decreases

$$\text{Energy absorbed per fiber } WD = \frac{\pi * d^2 * \sigma_f^2 * l_{cr}}{48 * E_f}$$

Toughening mechanisms

Fiber pull-out



Occurs as the proceeding of a debonding event

The energy needed for fibers to move away from their original locations is absorbed from the growing crack

Toughening mechanisms

Fiber pull-out

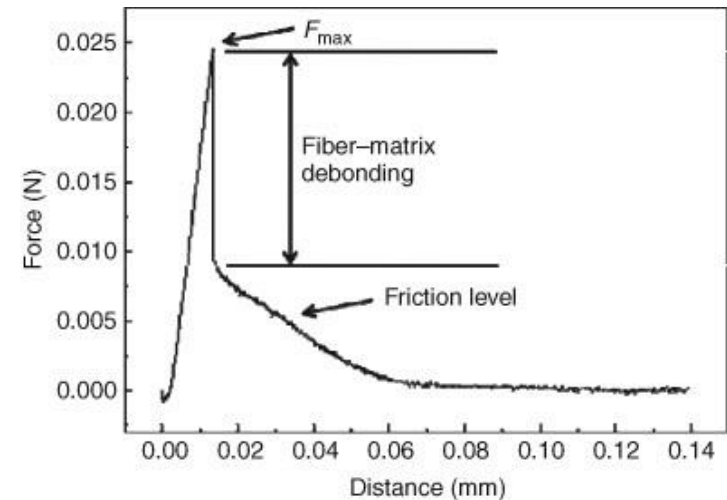
Only short fibers can be pulled out

Continuous fibers fracture after debonding (extra energy absorption). Fractured long fibers can be pulled out then

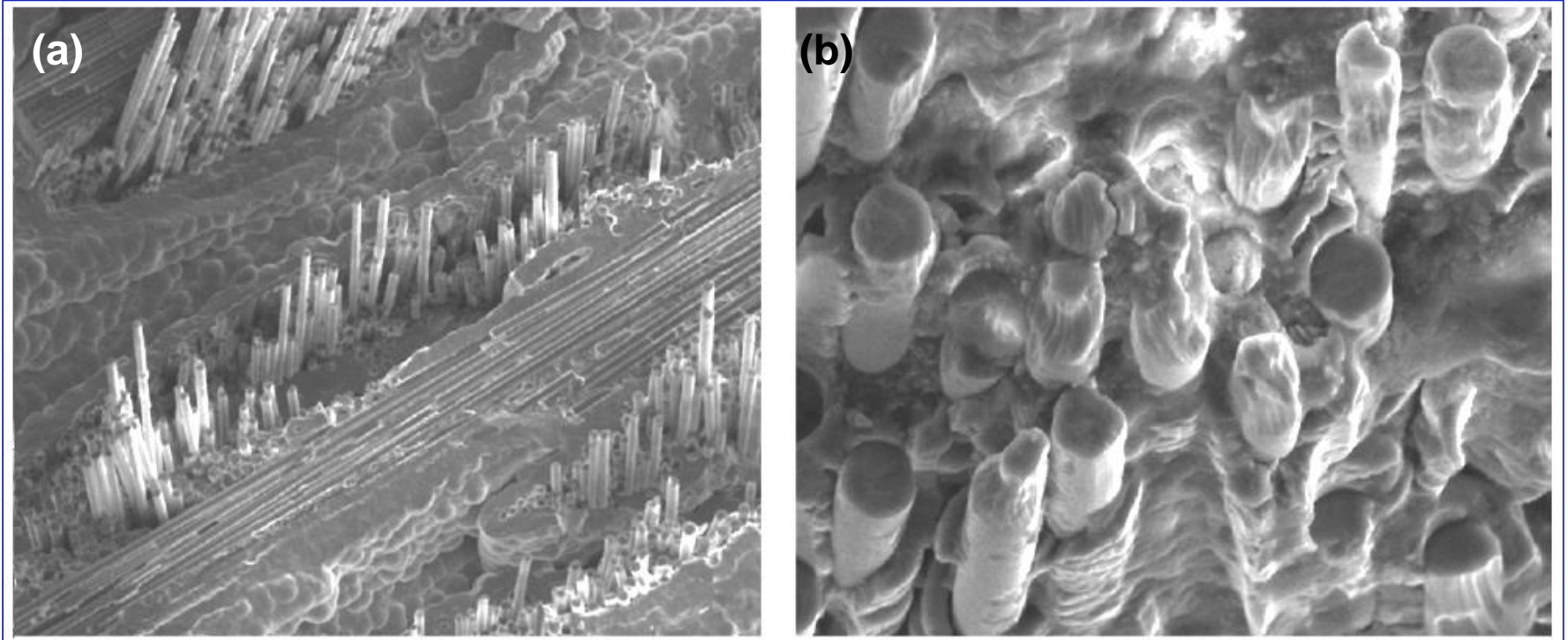
Hence long fibers are more effective in increasing toughness

Pullout work per fiber $WP = \frac{\pi*d^2*\sigma_f*l_{cr}}{16}$

Always $WP/W_D = \frac{3*E_f}{\sigma_f} > 1$

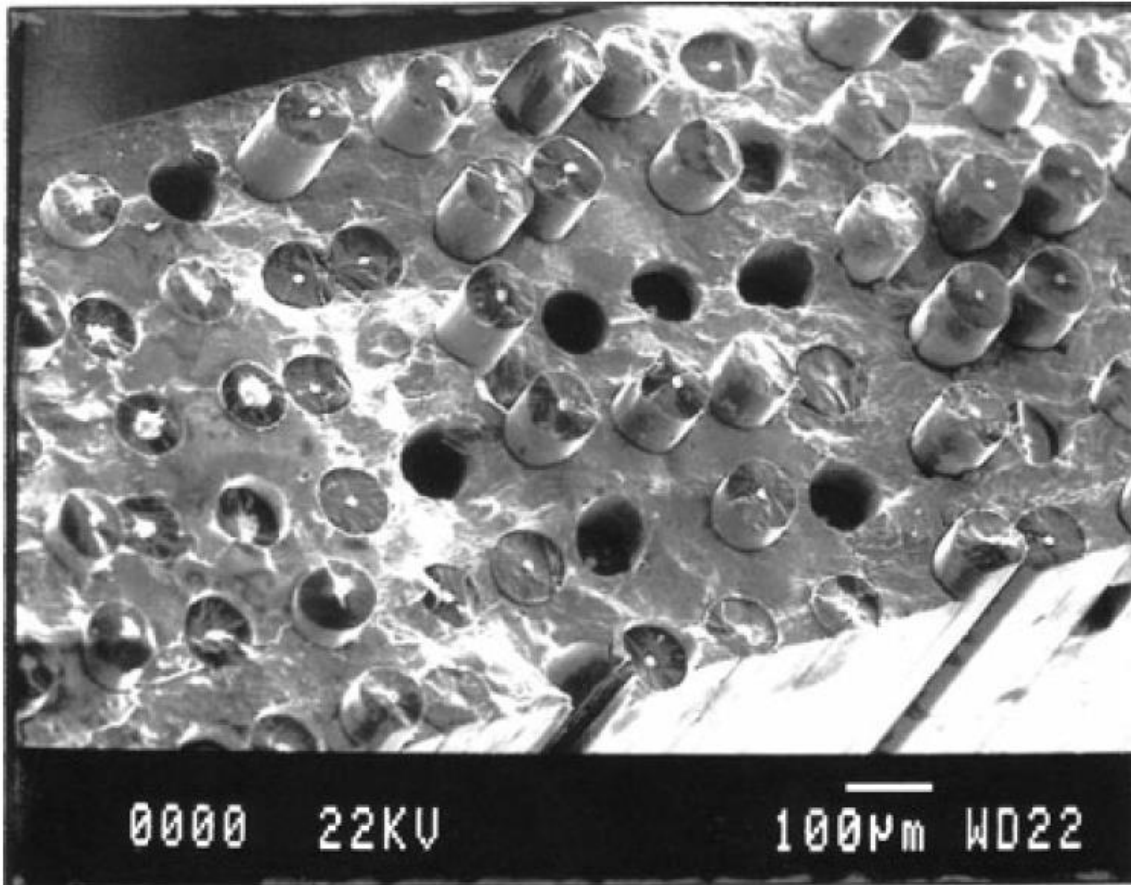


Toughening Mechanisms



Fatigue failure surfaces showing (a) fibre pull out and (b) wear of fibres

Toughening Mechanisms

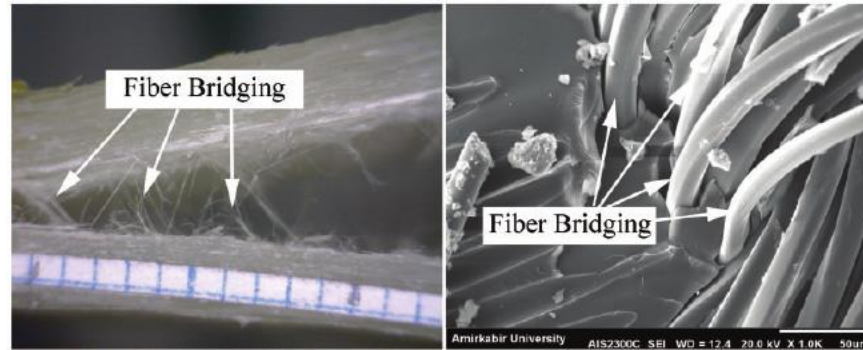


Bridging crack growth mechanism in SiC fiber-reinforced Ti-metal matrix composite illustrating fiber pull-out, fiber fracture, fiber/matrix interface debonding and matrix cracking. Fatigue crack growth test at 500°C, 10 Hz.

Tamin, M.N., Ghonem, H.: Fatigue Damage Mechanisms of Bridging Fibers in Titanium Metal Matrix Composites. J. Eng. Mater. Technol. Trans. ASME 122, 370–375 (2000)

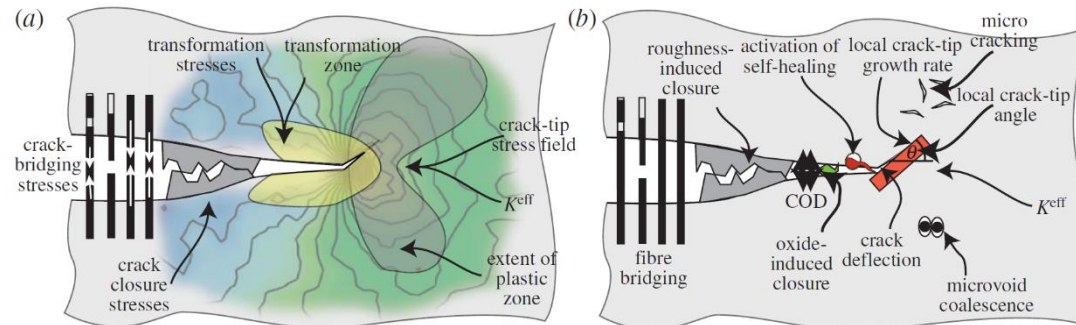
Toughening mechanisms

Fiber bridging



Strong fibers carry load after crack debonding

Particulate bridging is called crack wake toughening

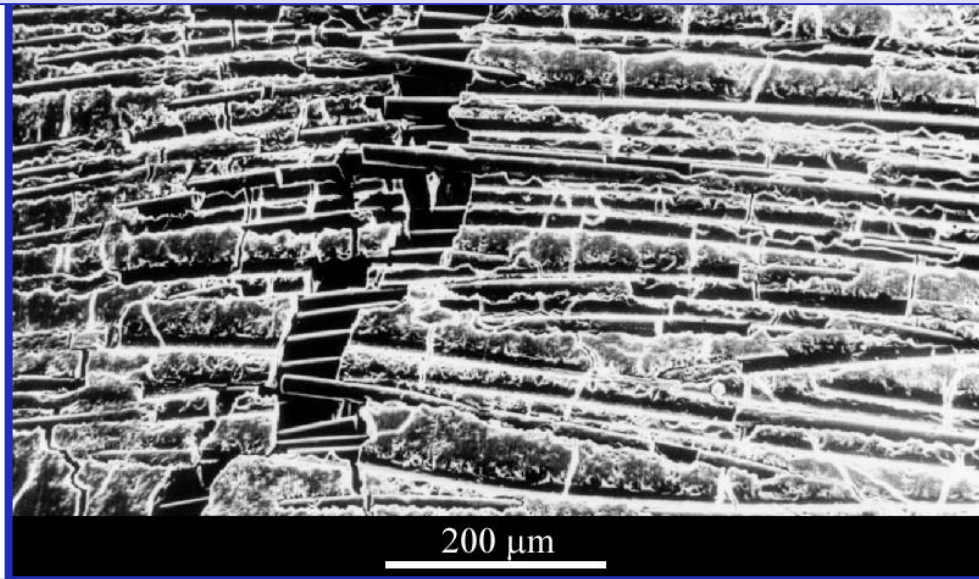


Here particles introduce roughness which decreases the crack growth rate to some extent

Toughening Mechanisms

The secondary phases are chosen to act as barriers to crack propagation.

Whiskers introduced into a ceramic matrix, for example, can retard the crack propagation because the stresses in a whisker spanning the crack plane will tend to pull the crack shut. This phenomenon, known as "crack bridging", leads to higher fracture toughness due to the additional stress required for further propagation of the crack. Moreover, continuous fiber composites exhibit quasi-ductile fracture behavior resulting from extensive fiber bridging.



Fractograph showing extensive matrix cracking and fibres bridging an opened matrix in a fibre reinforced magnesium aluminosilicate ceramic .

Toughening Mechanisms

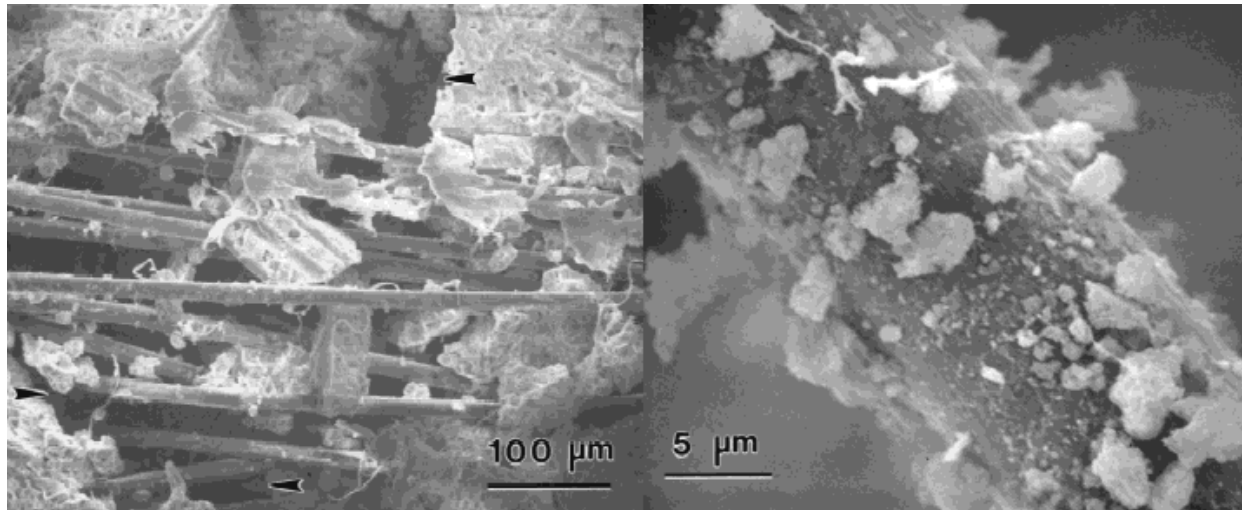
Cements are frequently toughened by addition of polymer fibers due to the advantage of room temperature synthesis

Three mechanisms of fiber reinforcement appeared to be operative in macroporous CPC composites:

First, when the matrix cracked under stress, the fibers bridged the crack to resist its further opening and propagation. The aramid fibers used in this study possessed a high tensile strength and were not cut through by the cracks. Weaker fibers were less effective in this kind of reinforcement.

Second, crack deflection by the fibers caused multiple cracking in the matrix. In comparison, CPC without fibers failed by a single crack with a flat fracture surface. Multiple cracking produced numerous fractured pieces of the matrix, consuming the applied energy in creating new surfaces, thus contributing to the toughness.

Third, the frictional sliding of fibers against the matrix during pullout further consumed the applied energy and further increased the fracture resistance of the composite. The effectiveness of the fiber in this composite was dependent on fiber type, fiber volume fraction, and fiber length



Toughening Mechanisms

Addition of carbon, aramid, e-glass and polyglactin fibers to calcium phosphate cements

Fiber reinforcement resulted fourfold increase in strength of CPC composite and an increase of nearly two orders of magnitude in work-of-fracture. The results showed that for each fiber, the ultimate strength generally increased with volume fraction and length. The ultimate strength and work-of fracture first increased with fiber length; the ultimate strength then slightly decreased at 200 mm fiber length, while the work-of-fracture leveled off at fiber length > 25 mm.

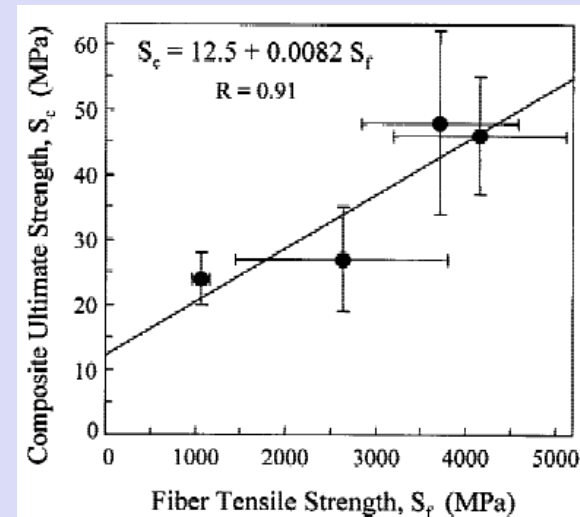
A valid correlation for the elastic modulus of the composite, for randomly oriented short fibers:

$$E_c = (3/8) E_L + (5/8) E_T$$

$$E_L = E_m [1 + \eta_L V_f (2L/d)] / [1 - \eta_L V_f]$$

$$E_T = E_m [1 + 2 \eta_T V_f] / [1 - \eta_T V_f]$$

where E_L and E_T are moduli of unidirectional shortfiber composites in the longitudinal and transverse directions, E_c , E_f , and E_m are elastic moduli of composite, fiber, and matrix, respectively. V_f is fiber volume fraction, L is fiber length, and d is fiber diameter.



Toughening Mechanisms

An empirical equation that relates the cement strength as a function of fiber strength:

$$S_C = S_m + aS_F$$

This is further refined as

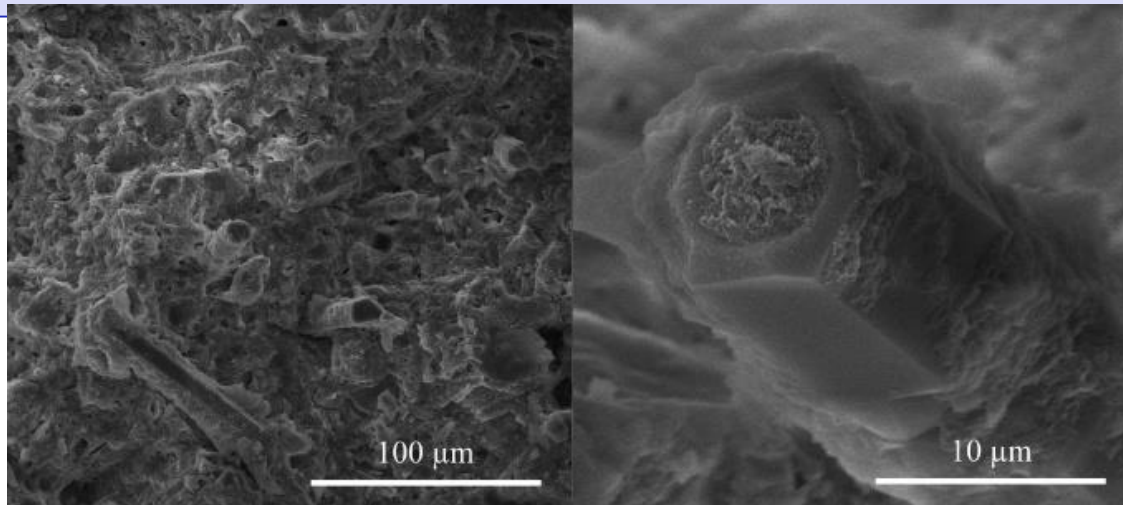
$$S_C = S_m + \beta S_m S_F = S_m(1 + \beta S_F)$$

When the fiber type, fiber length and fiber volume fraction were kept constant, the composite strength increased linearly when the matrix strength was increased and the calcium phosphate cement composite strength was, in general, 2.16 times higher than the strength of calcium phosphate cement without fibers

Xu investigated the relationship between fiber strength and composite strength and came up with the equation:

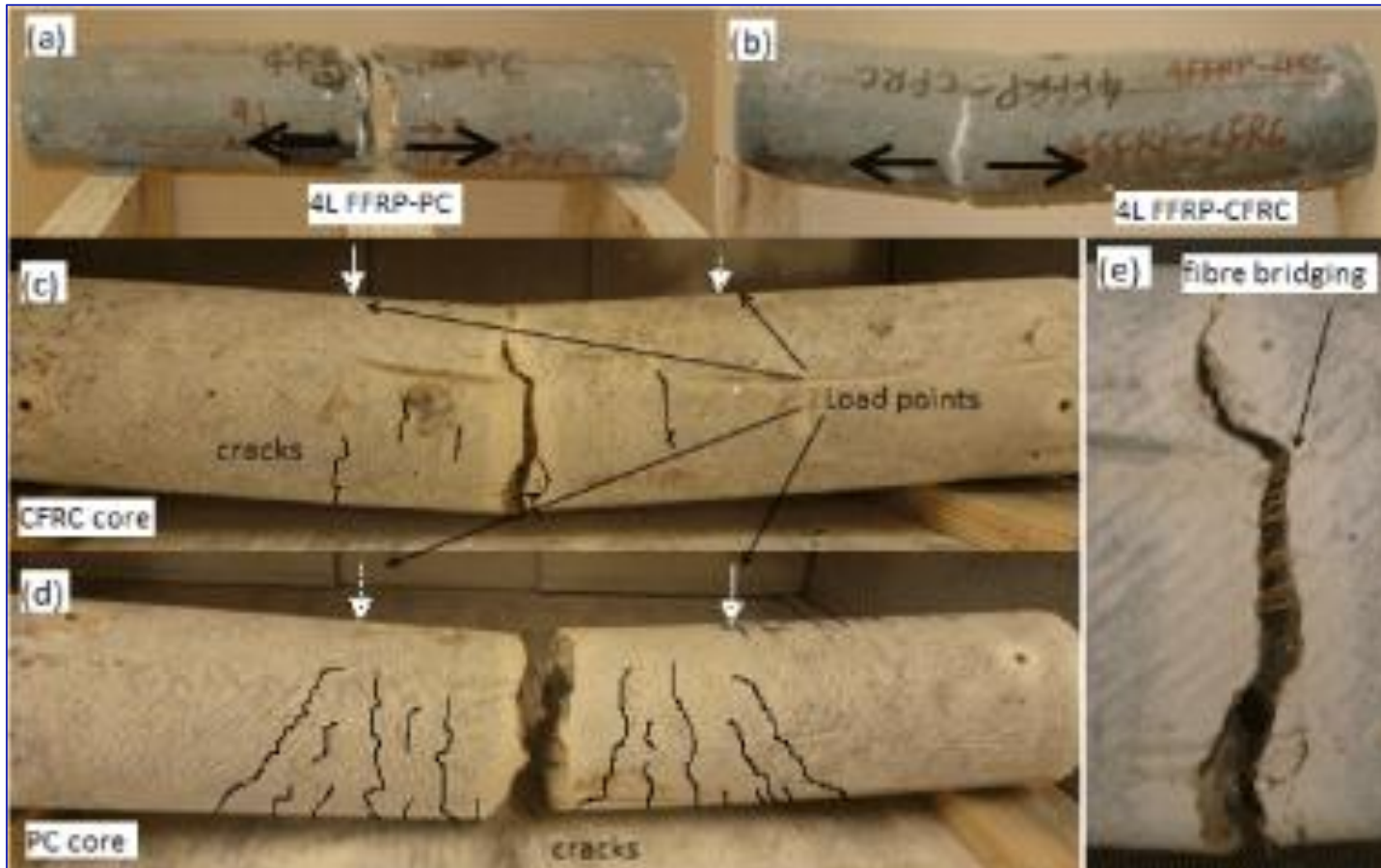
$$S_C = 14.1 + 0.047 S_F$$

This equation shows that a key to increasing the cement composite strength is to develop stronger fibers.



Scanning electron microscopy images of fractured surfaces of hydroxyapatite whisker-reinforced calcium phosphate cement

Toughening Mechanisms



Typical failure modes: (a) 4-layer FFRP-PC, (b) 4-layer FFRP-CFRC, (c) CFRC core, (d) PC core and (e) coir fibre bridging.

Toughening mechanisms

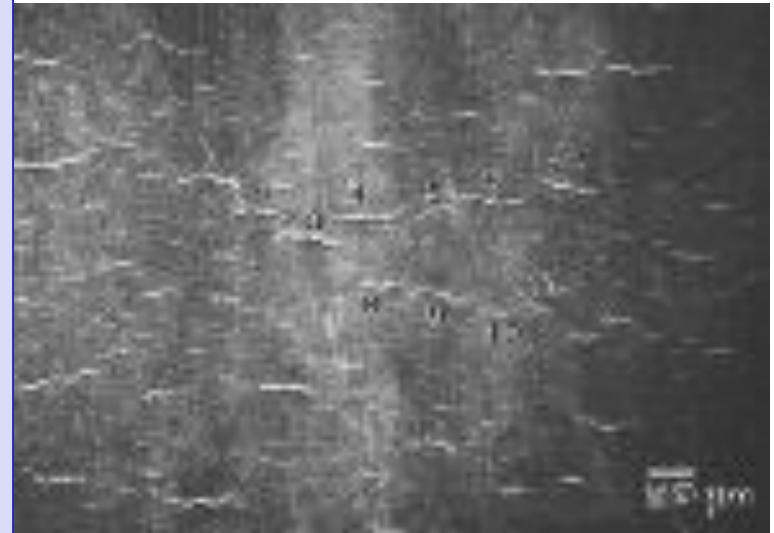
Micro-cracking

Small cracks occur mostly in CMCs due to the mismatch in thermal expansion coefficients of the fiber and matrix during cooling in production

These do not occur in PMCs and MMCs because small amount of deformation or annealing absorb thermal stresses in these materials

Microcracks in CMCs cause branching, blunting or deflection of macrocracks

Too many microcracks may combine to form macrocracks which decrease the strength of the matrix



Toughening Mechanisms

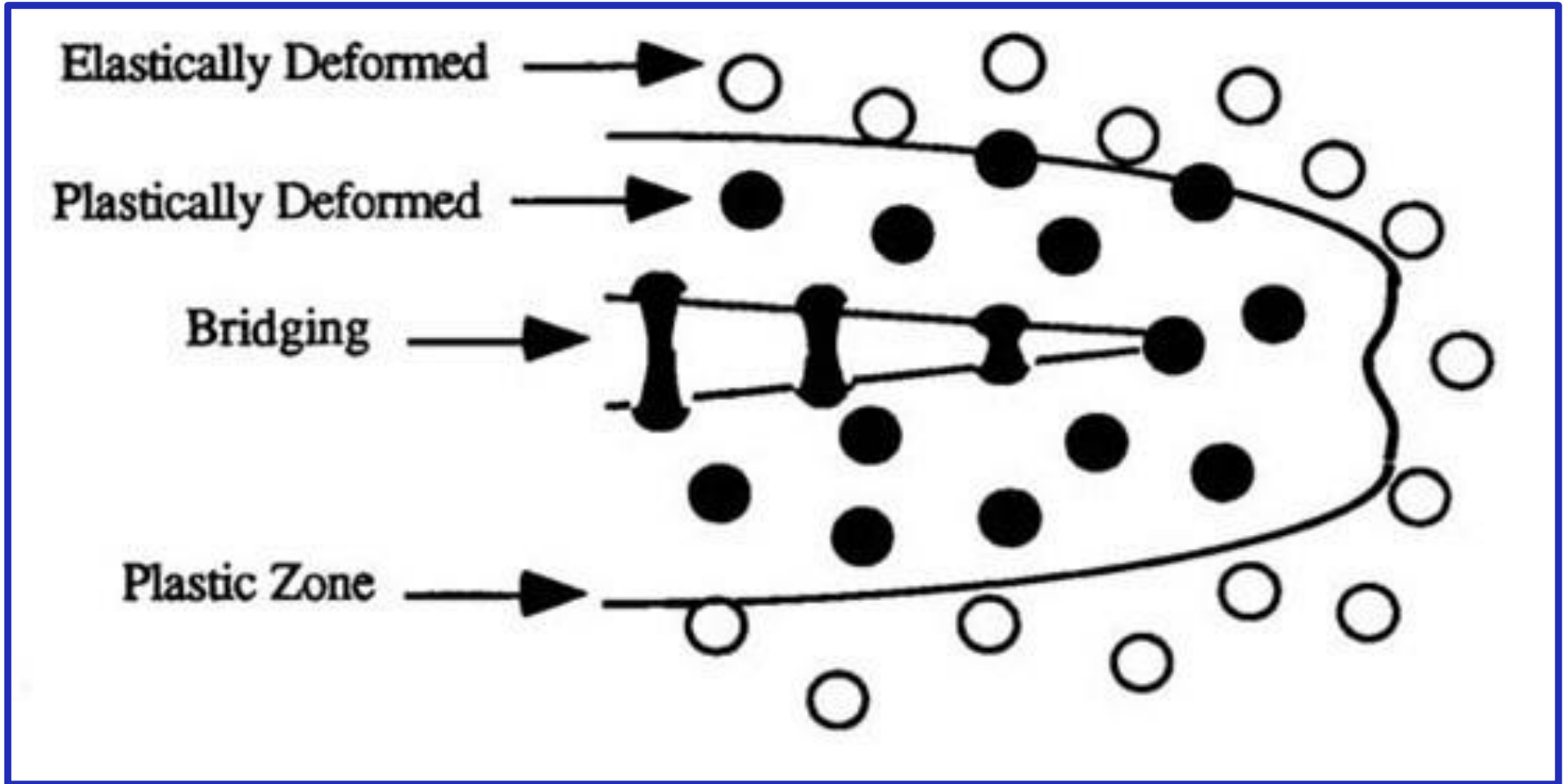
If α_R for a particulate reinforcement is greater than that for the matrix α_M then the circumferential cracks may be produced in the matrix, and for $\alpha_R < \alpha_M$ radial cracks may be found.

With a fibre reinforcement, when $\alpha_R > \alpha_M$ the axial tensile stresses induced in the fibres produce an overall net residual compressive stresses in the matrix and, as the fibres contract, there is a tendency for them to pull away from the matrix.

The stress situation is reversed when $\alpha_R < \alpha_M$ and cracking of the matrix due to the axial tensile stresses may occur. Clearly there has to be some matching of the coefficients of thermal expansion in order to limit these problems.

Transformation Toughening by ZrO_2

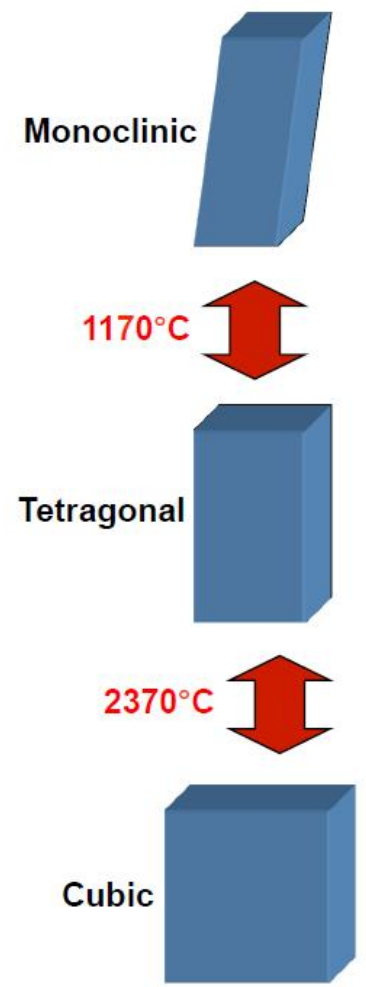
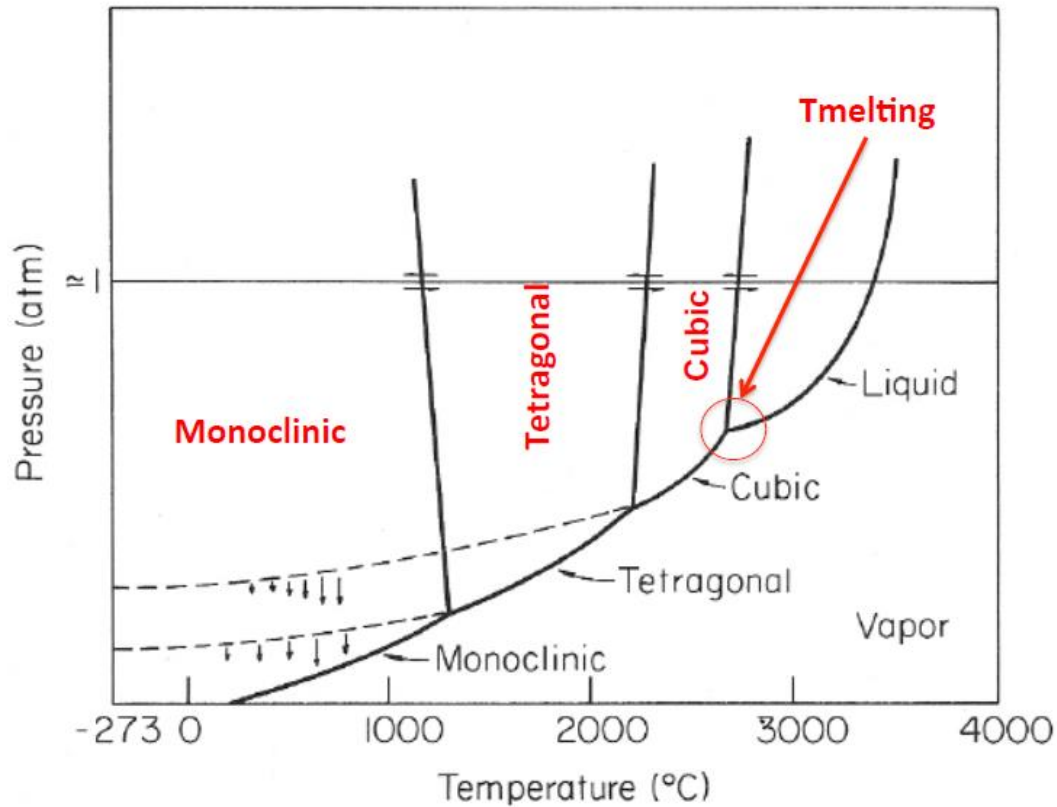
ZrO_2 is used commonly as a biomaterial due to its mechanical strength, as well as its chemical and dimensional stability and elastic modulus similar to stainless steel



Transformation Toughening by ZrO_2

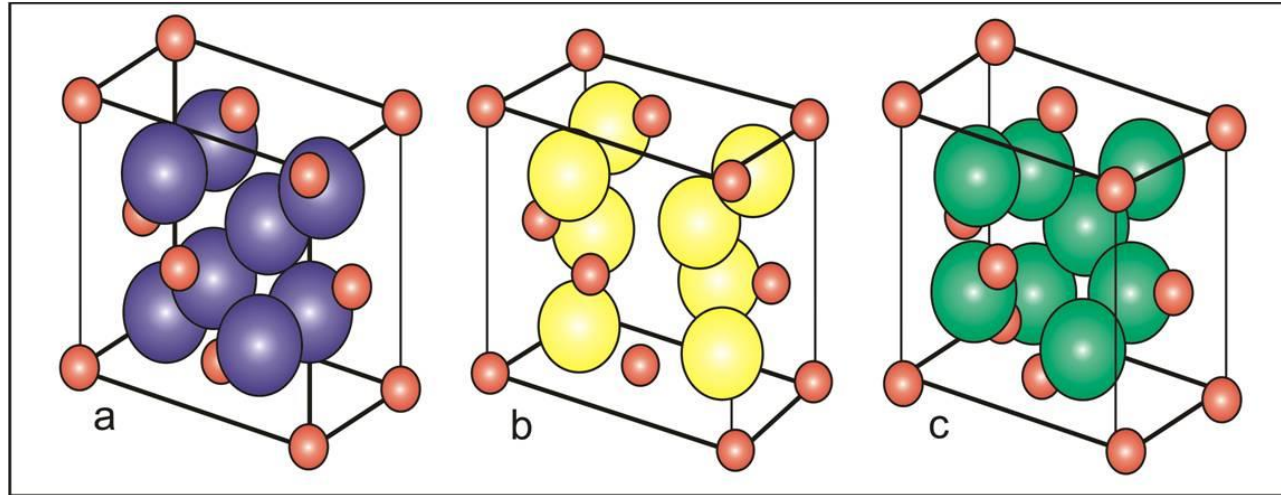
Phase Diagram for ZrO_2

One Component (Unary) System – (Zirconia - ZrO_2)



Transformation Toughening by ZrO_2

ZrO_2



Crystal structure of monoclinic (a), tetragonal (b) and cubic zirconia(c).

Depending on the temperature, zirconia can exist in three forms. Pure zirconia has a cubic structure at temperatures greater than $2,370^\circ \text{C}$. The cubic phase has a cubic form with square sides and moderate mechanical properties with a density of 6.27 g/cm^3 .

The tetragonal phase exists at temperatures ranging from $1,170^\circ \text{C}$ to $2,370^\circ \text{C}$. The tetragonal structure has a straight prism with rectangular sides and the most satisfactory mechanical properties with a density of 6.1 g/cm^3 .

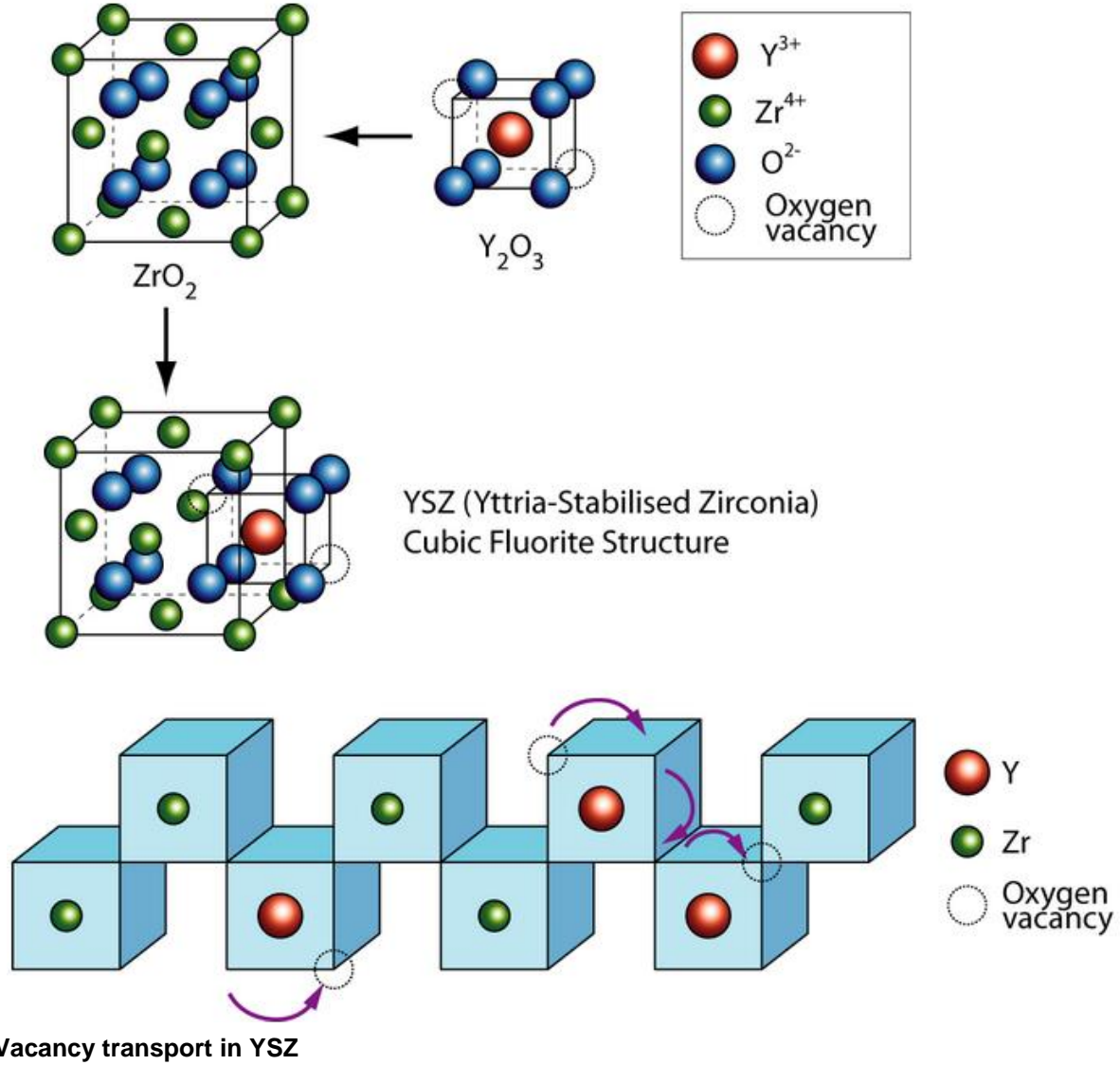
The monoclinic phase occurs at temperatures below $1,170^\circ \text{C}$ and has a deformed parallelepipedal (ie, a prism with six faces) shape, as well as the weakest mechanical properties with a density of 5.6 g/cm^3 .

Transformation Toughening by ZrO_2



In terms of strength, it is essential to limit the amount of the monoclinic phase because of its lower density.

To stabilize tetragonal zirconia at room temperature and control phase transformations, metal oxides, such as yttria (Y_2O_3) or ceria (CeO_2), are added to the crystal structure. The addition of "stabilizing oxides" yields multiphase materials called partially stabilized zirconia. Technically, if yttria is added for stabilization, then it is referred to as yttria-stabilized tetragonal polycrystals (Y-TZP).



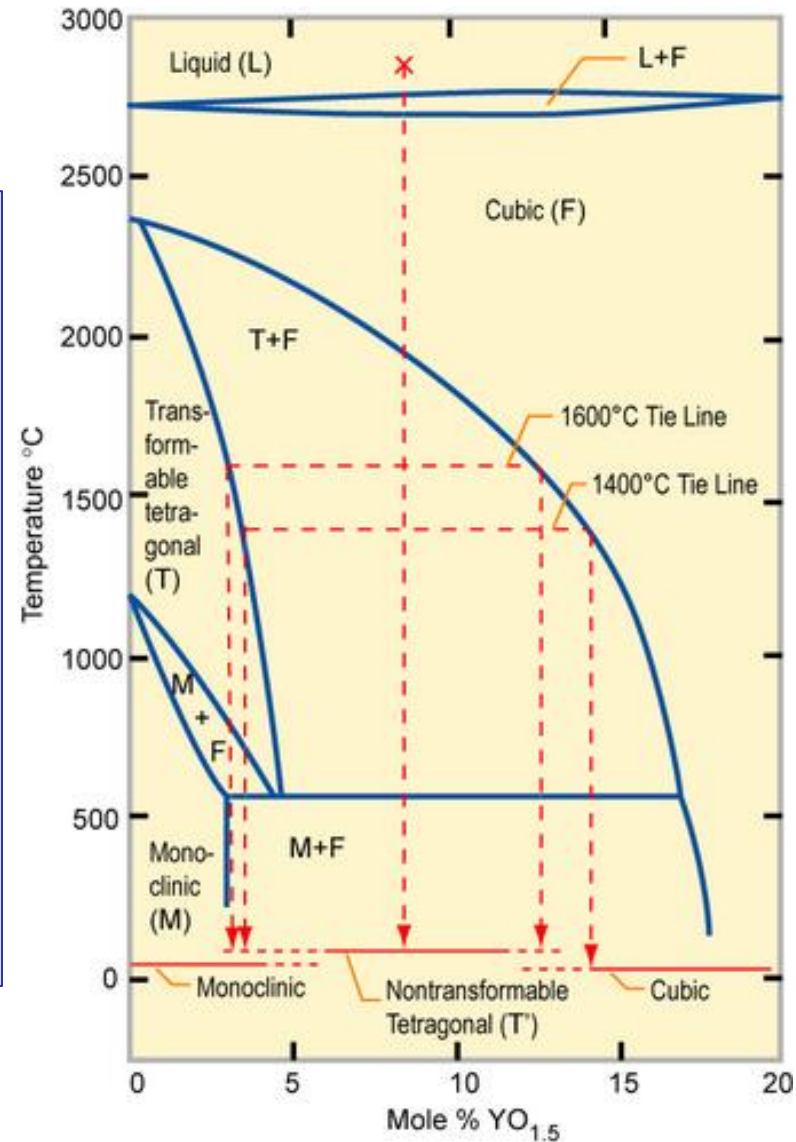
Vacancy transport in YSZ

Transformation Toughening by ZrO_2

ZrO₂

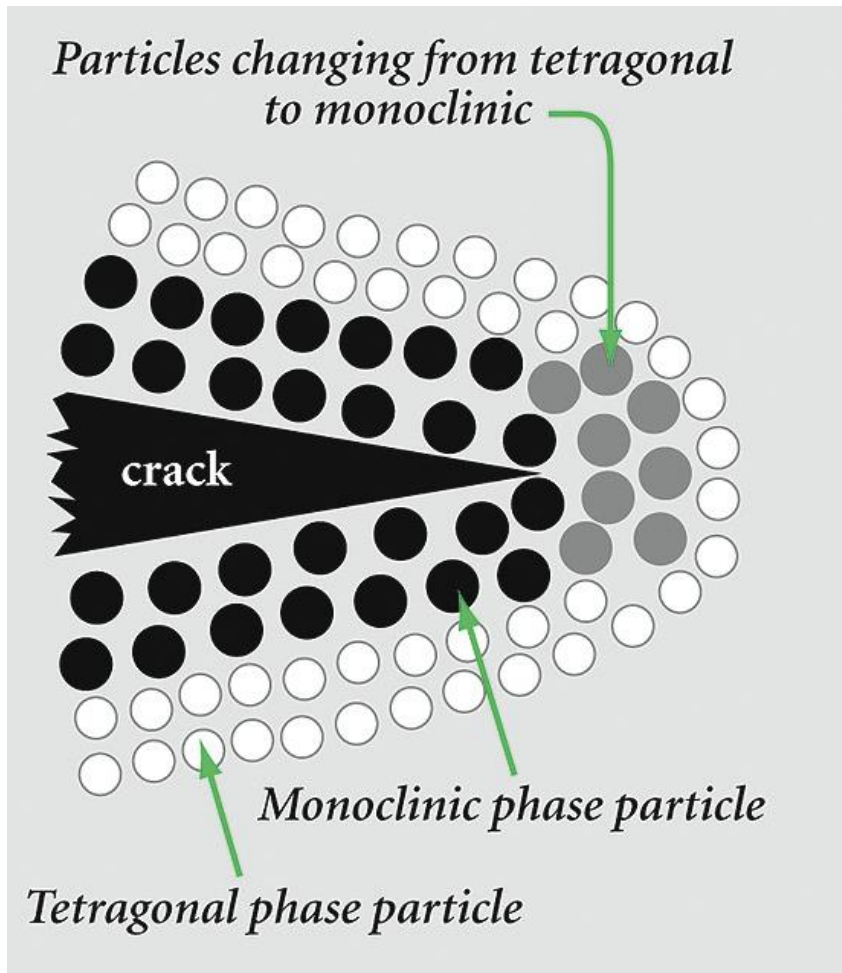
Phase diagram of partially stabilized zirconia (PSZ): Partially stabilized zirconia (PSZ) is a mixture of zirconia polymorphs: a cubic and a metastable tetragonal ZrO_2 phase is obtained, since an insufficient amount of stabilizer has been added. PSZ is a transformation-toughened material since the induced microcracks and stress fields absorb energy.

PSZ is used for crucibles because it has a low thermal conductivity and a high melting temperature. The addition of 16 mol% CaO or 16 mol% MgO or 8 mol% Y_2O_3 (8YSZ) is enough to form fully stabilized zirconia. The structure becomes cubic solid solution, which has no phase transformation when heating from room temperature up to 2500 °C.



Transformation Toughening by ZrO_2

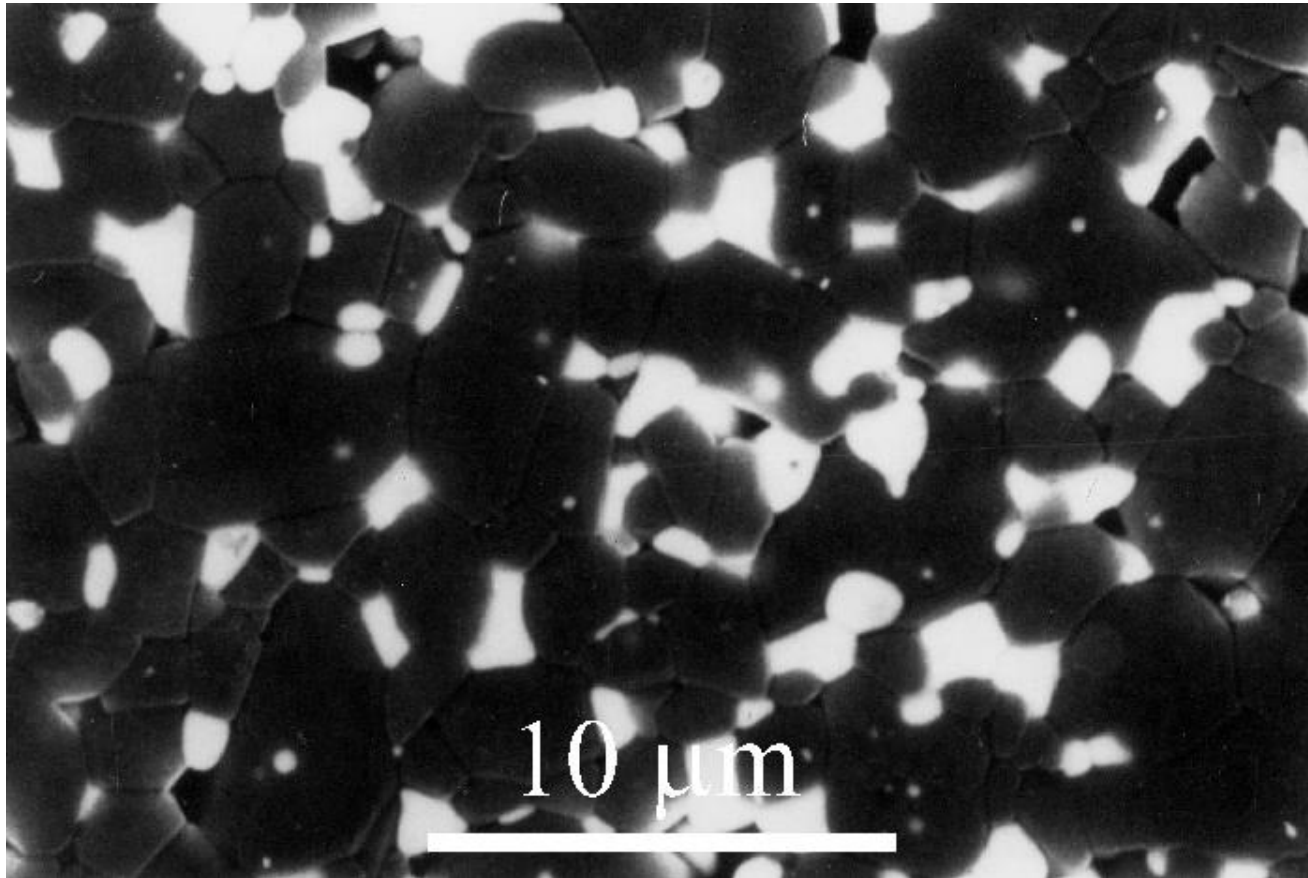
A unique characteristic of zirconia is its ability to stop crack growth, which is "transformation toughening".



An ensuing crack generates tensile stresses that induce a change from a tetragonal configuration to a monoclinic configuration and a localized volume increase of 3% to 5%.

This volume increase results in a change of tensile stresses to compressive stresses generated around the tip of the crack. The compressive forces counter the external tensile forces and stop the further advancement of the crack. This characteristic accounts for the material's low susceptibility to stress fatigue and high flexural strength of 900 MPa to 1,200 MPa.

Transformation Toughening by ZrO_2



The ZrO_2 addition to Al_2O_3 increases its toughness via the tetragonal to monoclinic ZrO_2 transformation, so called transformation toughening and microcracking. The bright zirconia can be inter- or intra-granular. Oxide powder mixtures are hot pressed or pressureless sintered at $<1600^\circ\text{C}$.

© DoITPoMS Micrograph Library, University of Cambridge.

Ceramic Matrix Composites

There is a wide spectrum of CMCs depending on the chemical composition of the matrix and reinforcement.

Non-oxide CMCs are those which have been the most studied.

Such a choice could appear surprising since the atmosphere in service is often oxidizing. That choice could be explained as follows. The **most performant fibres**, in terms of stiffness, failure strength, refractoriness and density **are non-oxide fibres**, i.e. carbon and silicon carbide fibres. Further, carbon fibres are extensively used in volume production of polymer-matrix composites. As a result, they are much cheaper than all the other fibres (except glass fibres).

Second, **in order to avoid compatibility problems**, which are crucial at high temperatures, non-oxide fibres are preferably embedded in non-oxide matrices. Hence, the first non-oxide CMCs have been carbon/carbon (C/C) composites. They have been initially designed and produced for use in rocket engines and re-entry heat shields, i.e. under extremely severe service conditions but short lifetimes. In a second step, C/SiC and SiC/SiC composites were developed in order to increase the oxidation resistance of the materials and hence their lifetimes in oxidizing atmospheres. Silicon nitride was also used as matrix although it is less stable at high temperatures than silicon carbide.

Ceramic Matrix Composites

Oxide-CMCs would obviously be the best choice, from a thermodynamic standpoint, for long term applications in oxidizing atmospheres.

Unfortunately, oxide fibres, although they are refractory, **tend to undergo grain growth** at high temperatures, (which results in a fibre strength degradation) and exhibit a poor creep resistance.

Further, they display **much higher densities** than for example carbon fibres (4 g/cm³ for alumina versus 2 g/cm³ for carbon).

Attempts have been made to improve the high temperature properties of oxide fibres with limited success. Despite these disadvantages, Al₂O₃/Al₂O₃ and derived CMCs have been, and are still, extensively studied.

Ceramic Matrix Composites

Effect of SiC-reinforcement fibers on the properties of selected ceramic materials

Material	Flexural Strength (psi)	Fracture Toughness (psi $\sqrt{\text{in.}}$)
Al ₂ O ₃	80,000	5,000
Al ₂ O ₃ /SiC	115,000	8,000
SiC	72,000	4,000
SiC/SiC	110,000	23,000
ZrO ₂	30,000	5,000
ZrO ₂ /SiC	65,000	20,200
Si ₃ N ₄	68,000	4,000
Si ₃ N ₄ /SiC	115,000	51,000
Glass	9,000	1,000
Glass/SiC	120,000	17,000
Glass ceramic	30,000	2,000
Glass ceramic/SiC	120,000	16,000

Ceramic Matrix Composites

Types of ceramic-matrix composites

- Al_2O_3 - ZrO_2 composites
- SiC particulate / Si_3N_4 matrix composites
- SiC whisker / Al_2O_3 matrix composites
- SiC whisker / Si_3N_4 matrix composites
- Continuous fiber / glass matrix composites
- Carbon / carbon composites
- SiC / SiC composites
- Oxide / oxide composites.

Ceramic Reinforcements

*Properties of selected reinforcing materials**

Material	Density (g/cm ³)	Tensile Strength (ksi)	Modulus of Elasticity (× 10 ⁶ psi)	Melting Temperature (°C)	Specific Modulus (× 10 ⁷ in.)	Specific Strength (× 10 ⁶ in.)
Polymers:						
Kevlar™	1.44	650	18.0	500	34.7	12.5
Nylon	1.14	12	0.5	249	1.0	2.9
Polyethylene	0.97	3–7	0.04–0.1	147	7.1	13.7
Metals:						
Be composites	1.83	40–50	44.0	1277	77.5	2.8
Boron	2.36	500	55.0	2030	64.7	4.7
W	19.40	580	59.0	3410	8.5	0.8
Glass:						
E-glass	2.55	500	10.5	<1725	11.4	5.6
S-glass	2.50	650	12.6	<1725	14.0	7.2
Carbon:						
HS (high strength)	1.75	820	40.0	3700	63.5	13.0
HM (high modulus)	1.90	270	77.0	3700	112.0	3.9
Ceramics:						
Al ₂ O ₃	3.95	300	55.0	2015	38.8	2.1
B ₄ C	2.36	330	70.0	2450	82.4	3.9
SiC	3.00	570	70.0	2700	47.3	5.3
ZrO ₂	4.84	300	50.0	2677	28.6	1.7
Whiskers:						
Al ₂ O ₃	3.96	3000	62.0	1982	43.4	21.0
Cr	7.20	1290	35.0	1890	13.4	4.9
Graphite	1.66	3000	102.0	3700	170.0	50.2
SiC	3.18	3000	70.0	2700	60.8	26.2
Si ₃ N ₄	3.18	2000	55.0		47.8	17.5

* $1 \frac{\text{gm}}{\text{cm}^3} = 0.0361 \frac{\text{lb}}{\text{in.}^3}$

Oxide Matrices

Comparative typical property guide for oxide matrices.

<i>Matrix</i>	<i>Crystal structure</i>	<i>Melting point in pure form, (°C)</i>	<i>Onset of reduction in reducing atmospheres, (°C)</i>	<i>Theoretical density, (Mg m⁻³)</i>	<i>Elastic modulus, (GPa)</i>	<i>Typical flexural strength, (MPa)</i>	<i>Thermal expansion coefficient, 10⁻⁶ K⁻¹ (25–1000 °C)</i>	<i>Thermal conductivity, W m⁻¹ K⁻¹ (25 °C)</i>	<i>Electrical conduction^c</i>
Alumina, Al ₂ O ₃	Hexagonal	2060	1400	3.986	400	300	8	≈ 38	Insulator
Y TZP ^a	Tetragonal	2300	400 (darkens)	6.10	210	800	10	≈ 1.5	Insulator/oxygen ion conductor
PSZ ^b	Cubic/ tetragonal	2300	400 (darkens)	6.05	200	500	10	≈ 1.5	Insulator/oxygen ion conductor
Mullite, 3Al ₂ O ₃ .2SiO ₂	Orthorhombic	1934	1000 (darkens)	3.1	300	250	5	≈ 10	Insulator
Yttrium aluminum garnet (YAG)	Cubic	2000	1400		280	250	8	≈ 15	Insulator
Spinel, MgO.Al ₂ O ₃	Cubic	2135	1400	3.59	280	250	8	≈ 15	Insulator
Na beta alumina	Hexagonal			≈ 3.5	320	300	8		Sodium ion conductor

^a TZP tetragonal zirconia polycrystals, containing a high proportion of metastable tetragonal ZrO₂, see Section 4.01.5.5. ^b PSZ partially stabilized zirconia, with insufficient stabilizer to form an all-cubic phase material, see Section 4.01.5.5. ^c Given in general descriptive terms; actual values are usually strong functions of composition, phase distribution, and temperature. Most oxides are electronic insulators. Those indicated become ionically conducting at raised temperature, typically above 300–400 °C.

Oxide Composites

Oxide matrices and typical useful reinforcements.

<i>Matrix</i>	<i>Particulates</i>	<i>Platelets</i>	<i>Whiskers</i>	<i>Fibers</i>
Alumina, Al ₂ O ₃	ZrO ₂ , SiC, TiC, TiN, TiB ₂ , ZrB ₂ , metals	SiC	SiC, B ₄ C	SiC, Al ₂ O ₃ , 3Al ₂ O ₃ .2SiO ₂
Y TZP ^a	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	
PSZ ^b	Al ₂ O ₃	SiC		
Mullite, 3Al ₂ O ₃ .2SiO ₂	Al ₂ O ₃ , ZrO ₂	Al ₂ O ₃	SiC	SiC, Al ₂ O ₃
Yttrium aluminum garnet (YAG)			Al ₂ O ₃	Al ₂ O ₃
Spinel, MgO.Al ₂ O ₃	Al ₂ O ₃			
Na beta alumina	ZrO ₂			

^a TZP tetragonal zirconia polycrystals, containing a high proportion of metastable tetragonal ZrO₂,

^b PSZ partially stabilized zirconia, with insufficient stabilizer to form an all-cubic phase material

Non-oxide Matrices

Comparative typical property guide for nonoxide matrices.

<i>Matrix</i>	<i>Crystal structure</i>	<i>Melting point in pure form (°C)</i>	<i>Onset of active oxidation (°C)</i>	<i>Theoretical density (Mg m⁻³)</i>	<i>Elastic modulus (GPa)</i>	<i>Typical flexural strength (MPa)</i>	<i>Thermal expansion coefficient, 10⁻⁶ K⁻¹ (25-1000°C)</i>	<i>Thermal conductivity W m⁻¹ K⁻¹ (25°C)</i>	<i>Electrical conduction^a</i>
SiC	α: hexagonal β: cubic	> 2200 (sublimes)	900 ^b	3.19	440	300	4	30	Insulator
Si ₃ N ₄	α, β: hexagonal	≈ 1750 (sublimes)	900 ^b	3.20	320	300-800	3	100	Insulator/ semiconductor
MoSi ₂	tetragonal	2030 (sublimes)	1000 ^b	6.25		380	8	60	Conductor
B ₄ C	rhombohedral	2420	800	2.52	450	350	5	30	Insulator
BN	hexagonal	> 2500 (sublimes)	800	2.27	40-60	40-60	7	20	Insulator
CVD // deposition							25	150	
CVD ⊥ deposition					150	150	0.4	2	
AlN	hexagonal (wurtzite)	> 2000 (decomposes)	900 ^c	3.26	350	400	5.6	> 150	Insulator
TiB ₂	hexagonal	2870	700	4.50	500	600	6		Conductor
TiN	cubic	2950 (sublimes in vacuum at > 1450)	700	5.44	450		8		Conductor
TiC	cubic	3065	700	4.92	460	800	8	30	Conductor

^a Given in general descriptive terms; actual values are usually strong functions of composition, phase distribution, and temperature. ^b Forms a passivating silica layer. ^c Forms a passivating alumina layer.

Non-oxide Composites

Nonoxide matrices other than carbon, and typical reinforcements.

<i>Matrix</i>	<i>Particulates</i>	<i>Platelets</i>	<i>Whiskers</i>	<i>Fibers</i>
SiC		SiC	B ₄ C	C, SiC
Si ₃ N ₄	SiC, TiC, TiN, TiB ₂	Si ₃ N ₄	Si ₃ N ₄	SiC, Al ₂ O ₃ , C
MoSi ₂	ZrO ₂ , TiB ₂ , Nb, SiC, Si ₃ N ₄	Al ₂ O ₃	SiC	SiC, Al ₂ O ₃
B ₄ C	TiB ₂ , Al ₂ O ₃	SiC	SiC	C, SiC
BN (hexagonal)	B ₄ C			
AlN			SiC	
TiB ₂	B ₄ C, BN			
TiN ¹				
TiC ¹				