Composite Materials

Reinforcement mechanisms in metal matrix composites

Reinforcement mechanisms in metal matrix composites

The deformation characteristics of metal matrix composites are determined by their microstructure and internal interfaces which are affected by their production history as well as many other parameters

The elements of the microstructure:

- Matrix structure – Chemical composition, grain size, texture, precipitation behavior and lattice defects determine the matrix structure

- Reinforcement structure – Reinforcement type, volume percentage, size, distribution and orientation determine the reinforcement structure

- Interface structure – Local varying tension due to the different thermal expansion behavior of two phases, wettability of the matrix, adhesion strength between the two phases determine the interface structure

Interface structure

A bond between the matrix and the reinforcement is needed to transfer stresses

The composite will be brittle if the bond is extremely strong because there will be no toughening mechanism

This is not a problem if toughness is already good, strong bonds increase the strength and stiffness of the composite

In addition to mechanical properties, thermal stability is determined by changes at the interfaces like reactions and precipitations

Composites offer improved thermal shock stability (especially against thermal fatigue)

Three bonding forms are possible:

1. Direct bonding between the two phases results in an interface

2. Another phase is added as interphase to improve the interfacial bond strength (e.g. silanes for glass fibers)

3. A chemical reaction, metallurgical phase transformation or diffusion results in an interphase. It is hard to control the effect

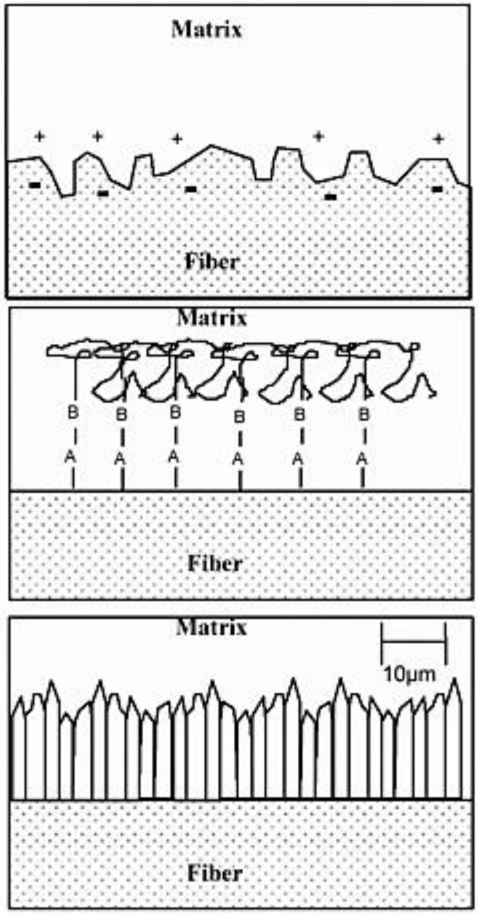
Interfacial bonding mechanisms

1. Mechanical bonding: Mechanical interlocking occurs between roughnesses in the matrix and reinforcement
   - Significant for only one application – concrete mechanically bonds to rough steel rods

2. Electrostatic bonding: Weak bonding between positively and negatively charged surface groups
   - Not significant for engineering applications

3. Chemical bonding: Ionic or hydrogen bonding either directly between the matrix and the reinforcement or through a coupling agent like silane
   - The most important type of bond for efficient stress transfer

4. Reaction bonding: Interdiffusion of both phases create a concentration gradient in the interface
   - Occurs in metals at high temperature, may be detrimental due to brittle intermetallics
   - Also intertwining of the carbon chains between two polymers cause branching, cross-linking



Wetting

Matrices infiltrate between the reinforcements in MMCs and most PMCs in liquid state

For good wettability the viscosity of the liquid material should be low

Also the wetting should be thermodynamically favorable:

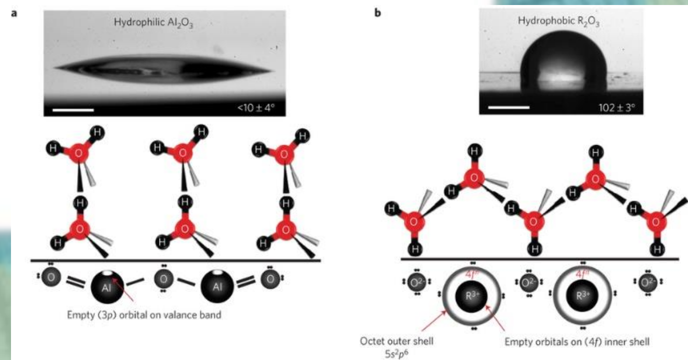
$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta$$

There is perfect wetting if the contact angle is 180

There is no wetting if the contact angle is 0

Between 0 and 180, there will be partial wetting

So for good wetting, $\gamma_{SG} > \gamma_{SL} + \gamma_{LG}$



Wetting

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta$$

Materials from the same class usually have similar surface energy levels

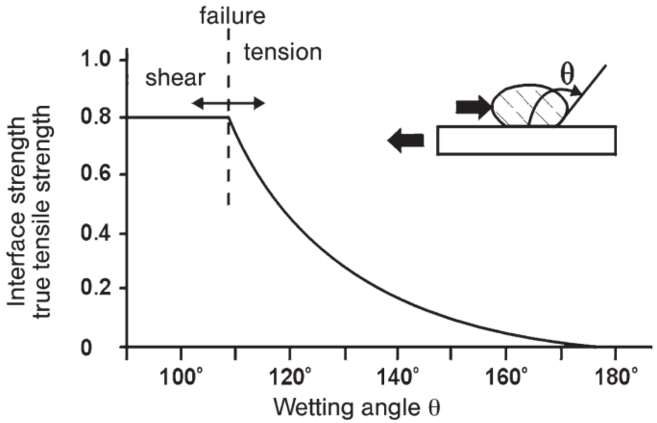
- Example – Epoxy resin with $\gamma_{LG} = 40\ mJ/m^2$ is reinforced with two types of fibers:

a. Alumina ($\gamma_{SG} = 1100\ mJ/m^2$)
b. Polyethylene ($\gamma_{SG} = 40\ mJ/m^2$)

Estimate the bonding strength in each composite

Adhesion

Adhesive strength of a solidified aluminum melt dropped on a substrate:



For small edge angles high adhesive strength values result in failure by shearing

Failure only occurs under tension at larger angles as the adhesive strength decreases

The adhesion in composite systems can also be improved by reaction

Reactions

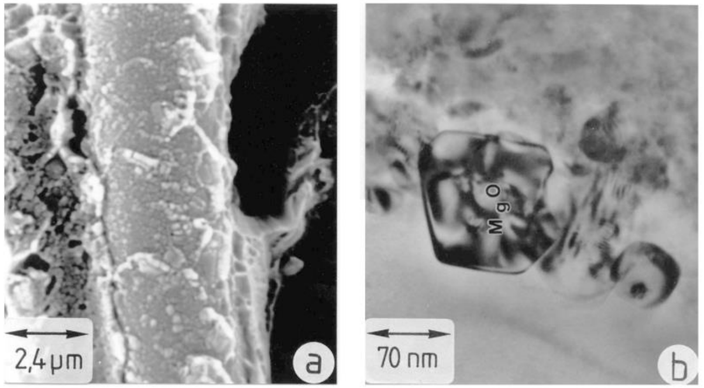
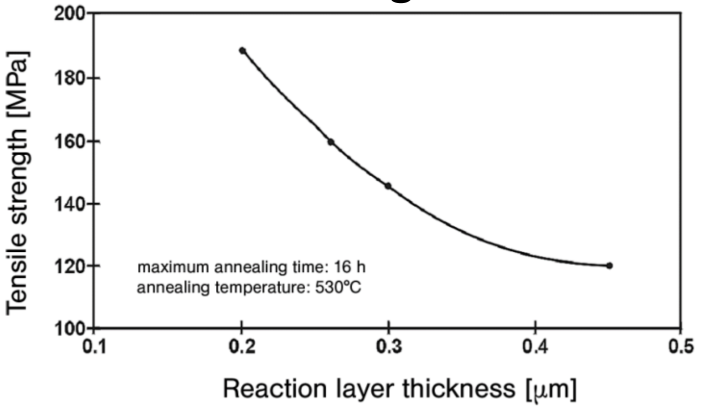


Fig. 1.42 Reaction products at the interface Mg alloy/Al_2O_3 fiber [53]: (a) SEM image, long term loading 350 °C, 250 h; (b)TEM image, as-cast condition.

Reactions between the matrix and the reinforcement phases may improve adhesion or result in damage to the reinforcement, resulting in reduction of the tensile strength of fibers

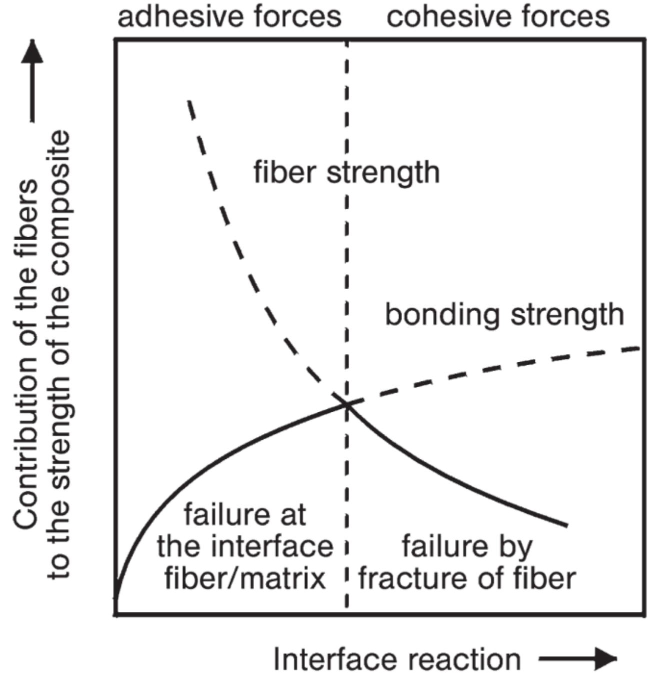
Annealing heat treatment on Mg alloy and alumina fiber interfaces results in fiber damage as the reaction product MgO particles grow at high T

The reaction layer thickness increases with time and temperature. The tensile strength of the composite decreases to 50% with increasing reaction layer thickness



Reactions

On the other hand, the bonding strength is improved with a reaction

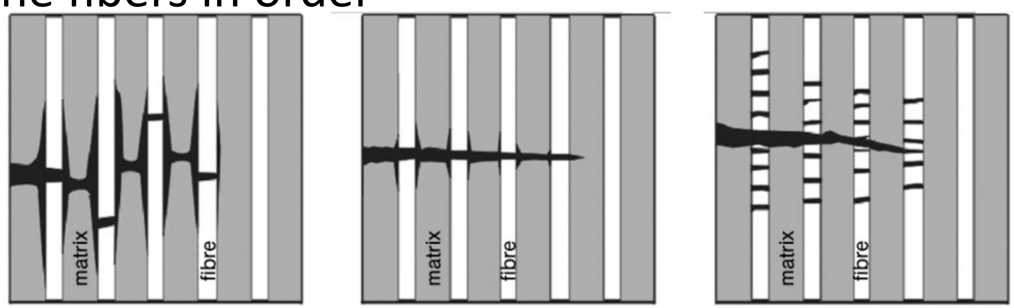


In case of poor binding the interface fails

In case of good binding fiber fails

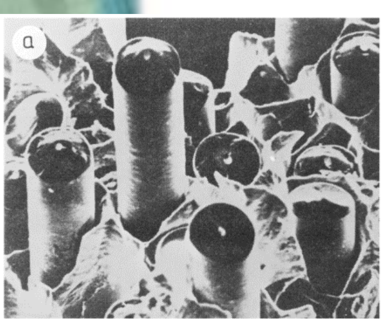
Adhesion

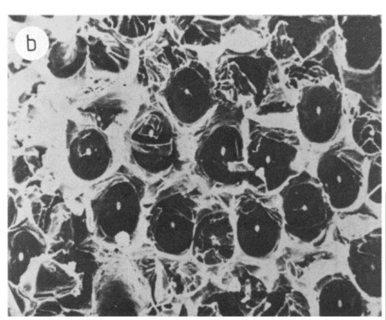
- Fiber pullout develops in case of weak binding as the crack moves along the fiber, the interface delaminates and the stress leads to the fracture of the fibers in order

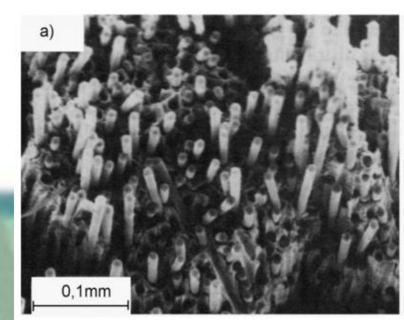


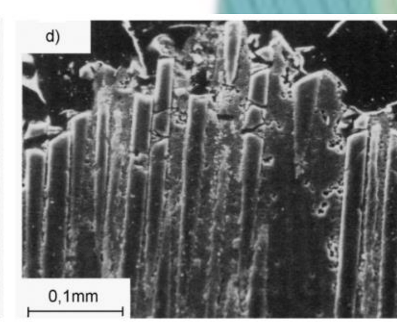
a) poor adhersion b) medium adhesion c) good adhesion

- For the case of good adhesion the fiber is fully loaded as the crack opens up due to the tensile stress, matrix deforms above and below the fiber fracture area and the fiber fractures in multiple positions





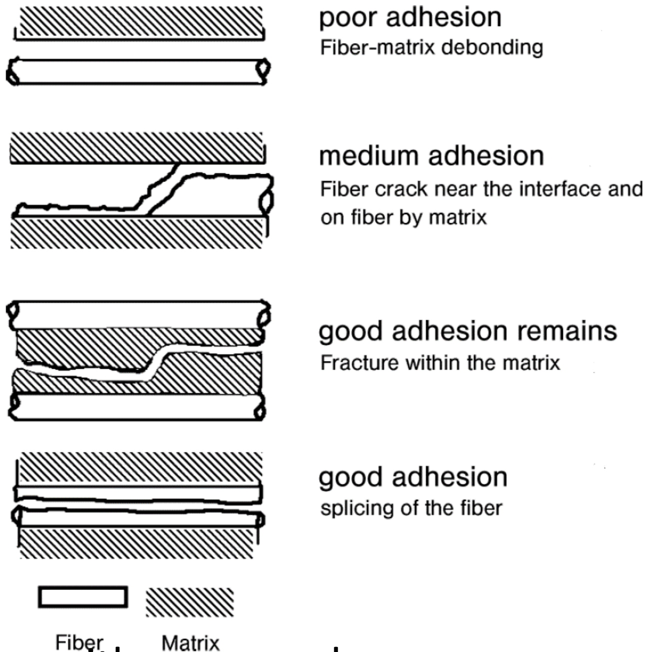




Adhesion

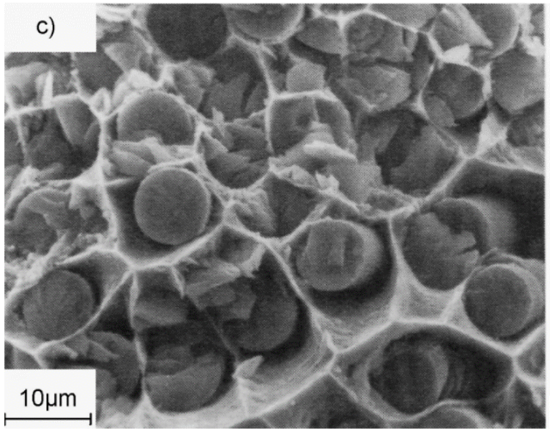
Different failure modes occur depending on the adhesion between the phases perpendicular to the fiber alignment (transverse pull strength)

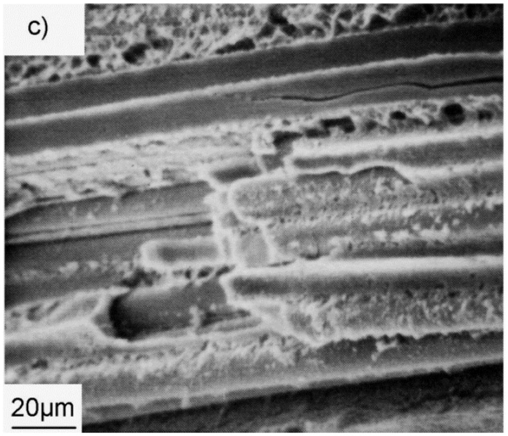
With very poor adhesion the fibers or particles work like pores and the strength is less than the nonstrengthened matrix



A failure occurs in the matrix or by disruption of the fiber with very good binding. The strength of the composite is close to the nonstrengthened matrix

A mixed fracture occurs at an average adhesion





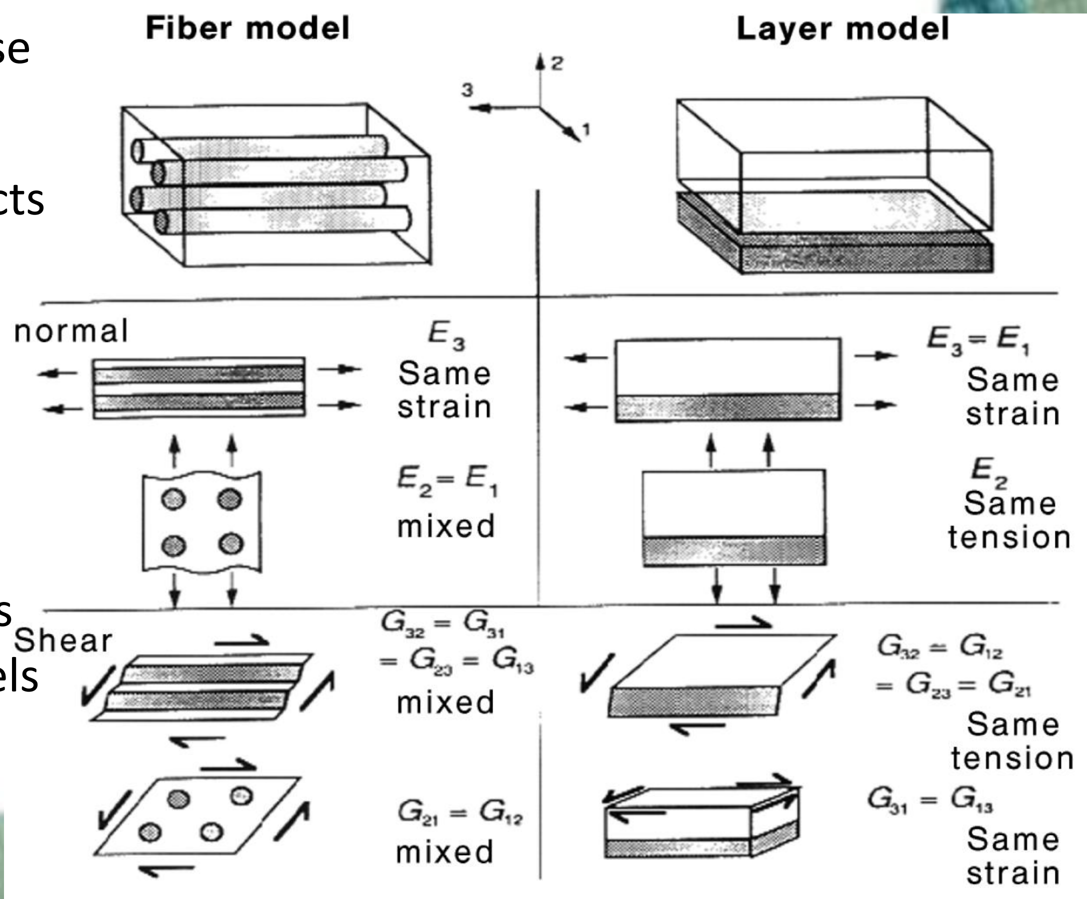
Effect of microstructure on properties

With knowledge of the characteristics of the elements of microstructure, it may be possible to estimate the properties of metal matrix composites.

Models are used for this purpose with the assumptions of

- very small number of contacts of the reinforcements among themselves
- comparable structures and precipitation behavior

In reality a strong interaction arises between the components involved, so the following models only indicate the potential of a material



Schematic presentation of elastic constants in composite materials

Effect of microstructure on properties

On the basis of these simple models an estimate can be made of the attainable strength of the fiber reinforced composite material for the different forms of the fibers

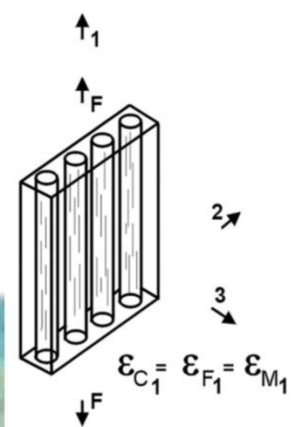
1. Long fiber reinforcement
   For the optimal case of a single orientation in the direction of the stress, no fiber contact and optimal interface formation, the linear rule of mixture can be used to calculate the strength of an ideal long fiber reinforced composite material in the axial direction:

$$\sigma_C = f_F * \sigma_F + (1 - f_F) * \sigma_{MY}$$

   Where σ_C is the strength of the composite, f_F is the fiber volume fraction, σ_F is the fiber tensile strength, σ_{MY} is the matrix yield strength

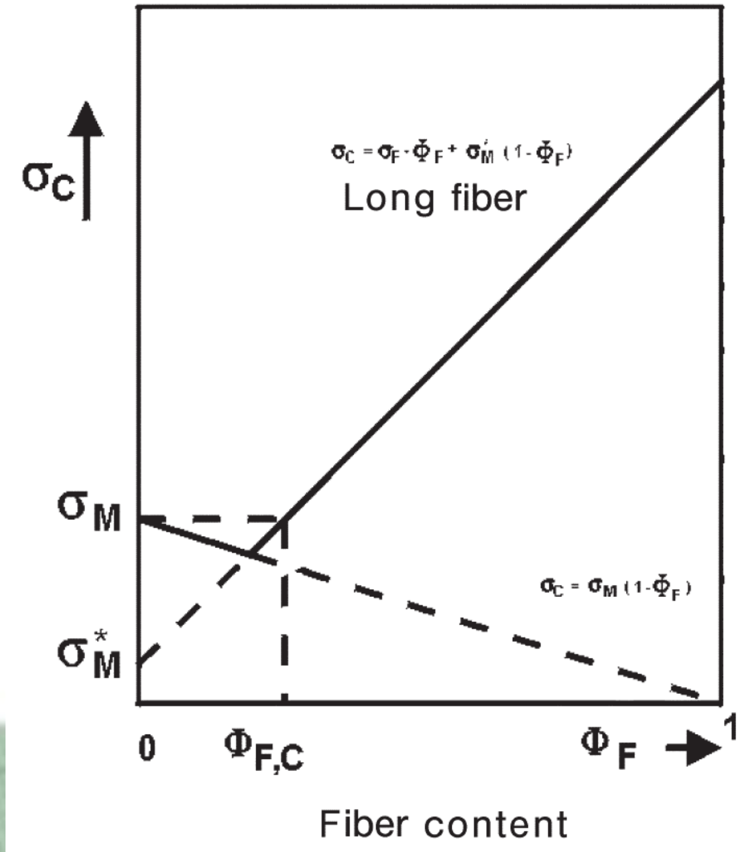
   A critical fiber content must be exceeded to reach an effective strengthening effect and it is obtained as

$$f_{F,crit} = \frac{\sigma_C - \sigma_{MY}}{\sigma_F - \sigma_C}$$



Effect of microstructure on properties

For unidirectional fiber composite with a ductile matrix and high strength fibers, the estimated variation of tensile strength with fiber content is given as follows



Effect of microstructure on properties

Different behavior of the composite results for different matrix-long fiber combinations

- Example – The stress-strain behavior of fiber composite with a ductile matrix whose tensile strength is larger than of the fibers

The deformation behavior is affected considerably by the fiber above the critical fiber content

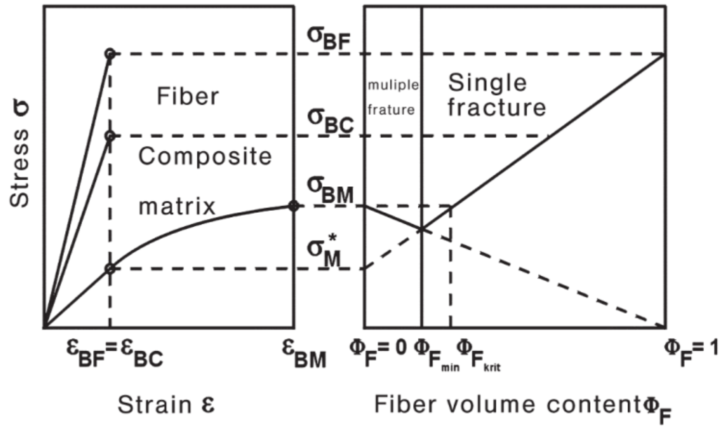


Fig. 1.14 Stress–strain behavior of a fiber composite material with a brittle matrix, which shows no strengthening behavior and whose elongation at fracture is smaller than that of the fibers (σ_{BF} = tensile strength of the fiber, σ^*_F = effective fiber strength at fracture of the composite material, σ_{BC} = strength of the composite material, σ_{BM} = matrix strength, ε_{BF} = elongation at fracture of the fiber, ε_{BM} = elongation at fracture of the matrix, ε_{BC} = elongation at fracture of composite material) [24].

Effect of microstructure on properties

Different behavior of the composite results for different matrix-long fiber combinations

- Example – The stress-strain behavior of fiber composite with a brittle matrix where no hardening arises and the elongation to fracture is smaller than those of the fibers

The material fails on reaching the strength of the matrix below the critical fiber content

A higher number of fibers can carry more load above this critical parameter, and a larger reinforcement effect develops

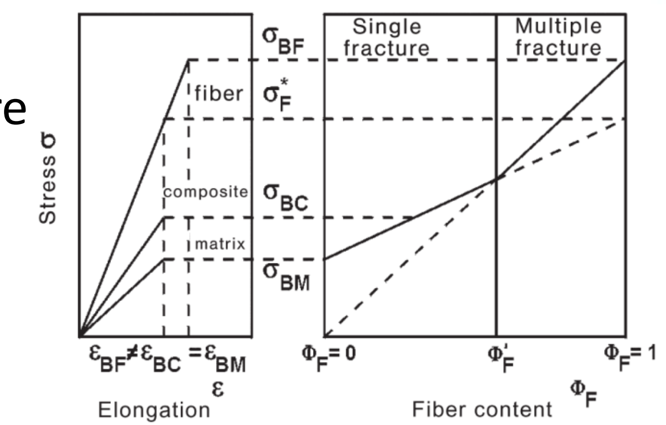


Fig. 1.13 Stress–strain behavior of a fiber composite material with a ductile matrix, in which elongation at fracture is higher than that of the fibers (σ_{BF}=tensile strength of the fiber, σ^{*}_{F}=effective fiber strength at the fracture of the composite material, σ_{BC}=strength of composite material, σ_{BM}=matrix strength, ε_{BF}= elongation at fracture of the fiber, ε_{BM}=elongation at fracture of the matrix, ε_{BC}= elongation at fracture of the composite material) [24].

Effect of microstructure on properties

Different behavior of the composite results for different matrix-long fiber combinations

In the case of a composite material with a ductile matrix and ductile fibers, where both undergo hardening during the tensile test, the resulting stress-strain curve can be divided into three ranges

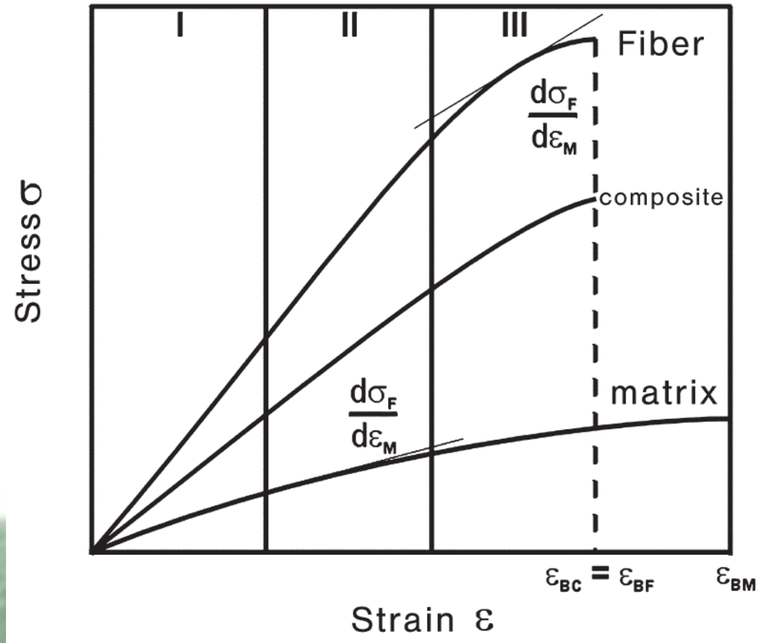


Fig. 1.15 Stress–strain behavior of fiber composite materials with a ductile matrix and fibers, both have strength in the tensile test (ε_{BF} = elongation at fracture of the fiber, ε_{BM} = elongation at fracture of the matrix, ε_{BC} = elongation at fracture of the composite material) [24].

Effect of microstructure on properties

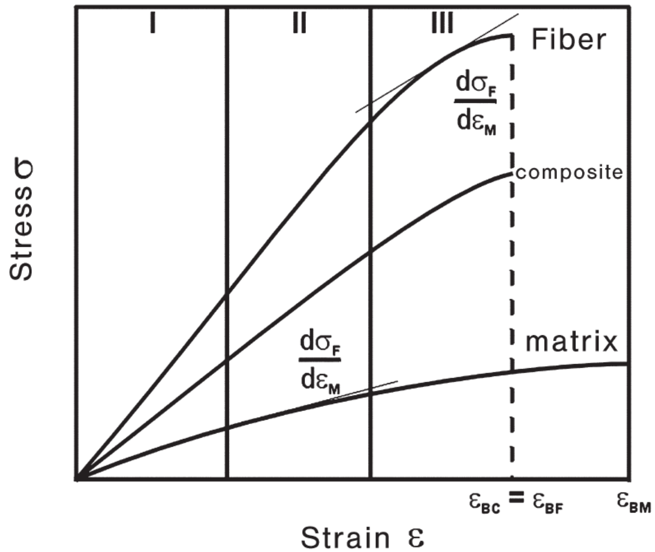


Fig. 1.15 Stress–strain behavior of fiber composite materials with a ductile matrix and fibers, both have strength in the tensile test (ε_{BF} = elongation at fracture of the fiber, ε_{BM} = elongation at fracture of the matrix, ε_{BC} = elongation at fracture of the composite material) [24].

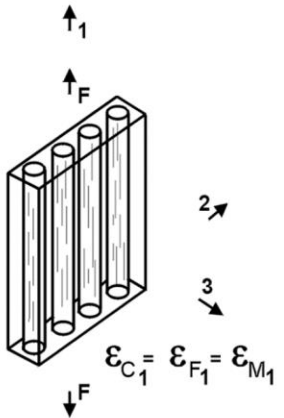
- Range I is characterized by the elastic behavior of both components
- Range II is where only the matrix shows a strain hardening and the fiber is elastically elongated
- In Range III both matrix and fiber show strain hardening behavior, the composite fails after reaching the fiber strength

Effect of microstructure on properties

2. Short fiber reinforcement

The effect of short fibers as reinforcement in MMCs is explained with the help of a micromechanical model. Especially important are the fiber length, fiber orientation and the fiber volume ratio

The model is based on the rule of mixture for the calculation of the axial strength for an ideal long fiber reinforced MMC. The same assumptions are considered again.



Effect of microstructure on properties

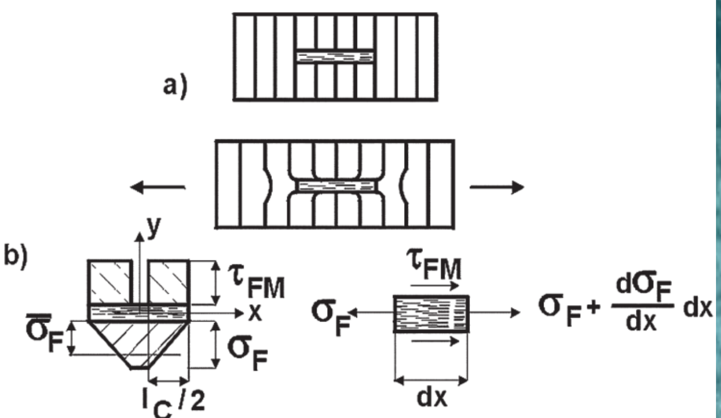
During loading of the short fiber reinforced MMCs, the individual fibers do not carry the full tension over their entire length. The effective tension on the fiber as a function of fiber length is majorly caused by shear stresses at the interface (τ_{FM})

$$\frac{d\sigma_F}{dx} * dx * \pi * r_F^2 + 2\pi * \tau_{FM} * r_F * dx = 0$$

$$\tau_{FM} = 0.5 * \sigma_{MY}$$

$$\sigma_F = \frac{2}{r_F} * \tau_{FM} * \left[\frac{2}{r_F} - x\right]$$

$$l_C = \frac{\sigma_F * r_F}{\tau_{FM}}$$



a) Strain field in the matrix
b) Shear strength at the interface fiber/matrix and tensile strength within the fiber

where σ_F is the fiber tension, r_F is the fiber radius, τ_{FM} is the stress at the fiber/matrix interface and l_C is the critical fiber length at which the fiber can be loaded to its maximum

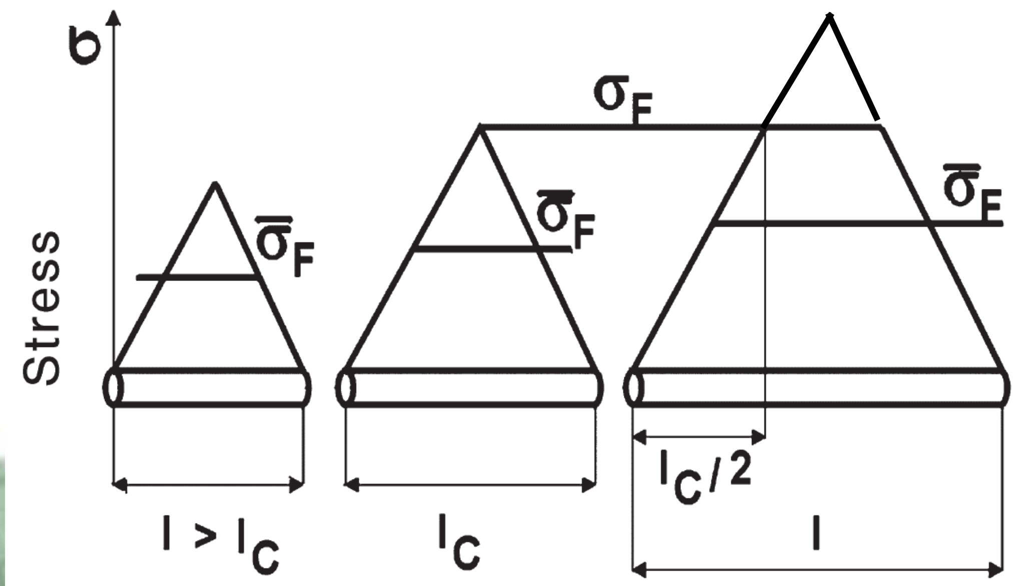
Effect of microstructure on properties

The effective fiber strength is given as a function of the fiber length as

$$\sigma_{Feff} = \eta * \sigma_F * \left(1 - \frac{l_c}{2 * l_m}\right)$$

Where $0 < \eta < 1$ is the fiber efficiency and l_m is the mean fiber length

Three cases of dependence of the effective
fiber strength on the fiber length are shown in the figure below



Effect of microstructure on properties

For the case of mean fiber length $l_m > l_c$, strength of the composite is estimated as

$$\sigma_C = \eta * C * f_F * \sigma_F * \left(1 - r_F * \frac{\sigma_F}{l_m * \sigma_{MY}}\right)$$

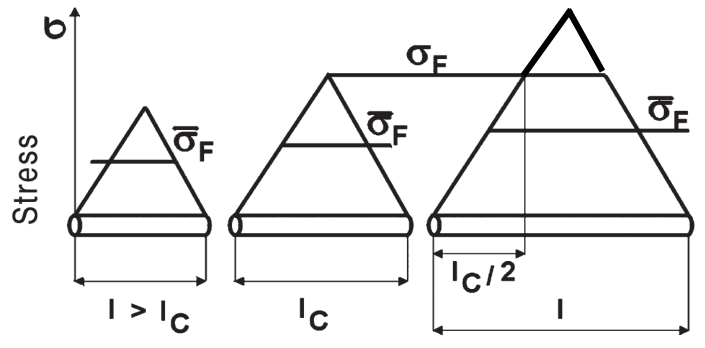
Where C is the orientation factor (C=1 for oriented fibers, C=3/8 for planar isotropic, C=1/5 for irregular

For the case of $l_m = l_c$

$$\sigma_C = \eta * C * 0.5 * f_F * \sigma_F * (1 - f_F) * \sigma_{MY}$$

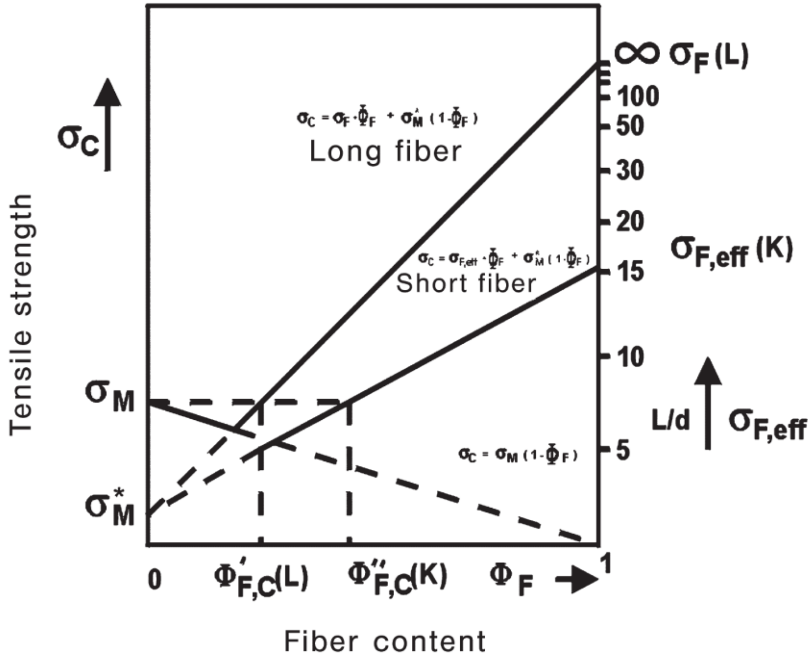
And for mean fiber length less than the critical length, the tensile strength of the fiber under load cannot be completely utilized

$$\sigma_C = \eta * C * 0.5 * \sigma_{MY} * \frac{l_m}{2 * r_F} + (1 - f_F) * \sigma_{MY}$$



Effect of microstructure on properties

The influence of the length/thickness relationship of the fibers on the reinforcement effect under optimal conditions:

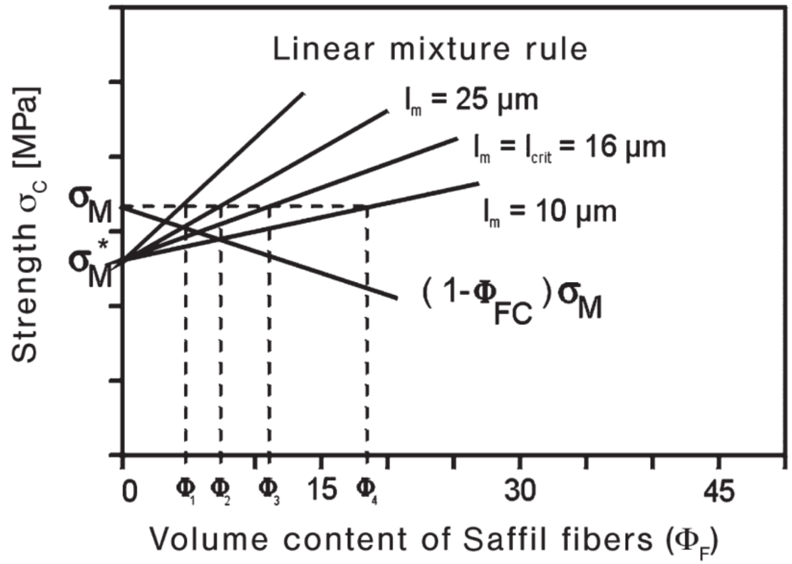


$$\sigma_{Feff} = \eta * \sigma_F * \left(1 - \frac{l_c}{2 * l_m}\right)$$

As the mean length of the fibers is increased, the reinforcement potential of long fibers (l/d>100) is reached

Effect of microstructure on properties

The relationship of the reinforcement effect (ratio of the strength of fiber reinforced light metal alloys to the strength of the non-reinforced matrix) as a function of the content of aligned fibers for different fiber lengths:

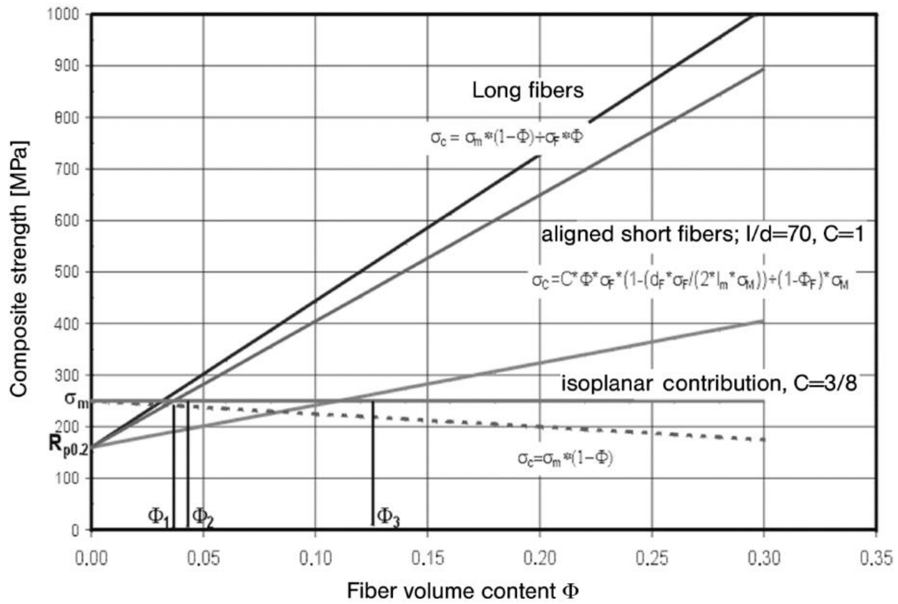


Matrix tensile strength: 340 MPa, yield strength: 260 MPa

Al_2O_3 fiber tensile strength: 2000 MPa, diameter: 3 micrometers

Effect of microstructure on properties

There is a smaller reinforcement effect with an irregular arrangement of fibers in the composite



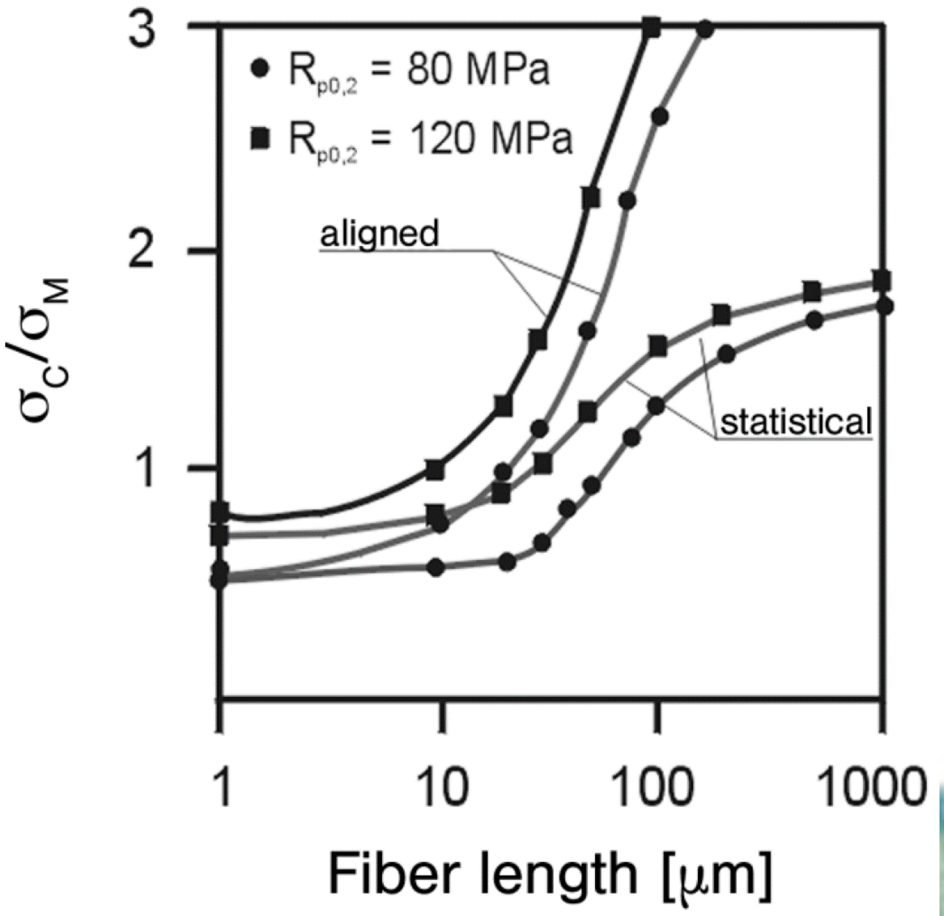
Magnesium matrix tensile strength: 255 MPa, yield strength: 160 MPa

C fiber tensile strength: 2500 MPa, diameter: 7 micrometers

With increasing isotropy more fibers are required for the same reinforcement effect

Effect of microstructure on properties

The long fibers reinforce significantly more than isotropic reinforcements at higher temperatures (less modulus)



Effect of microstructure on properties

3. Strengthening by particles

Ceramic particles in metals influence the mechanical properties by 4 mechanisms

1. Change in grain size (e.g. recrystallization during thermomechanical treatment), ($\Delta\sigma_G$)
2. Strain hardening around the particles ($\Delta\sigma_h$)
3. Induced dislocations due to thermal mismatch and geometrical constraints ($\Delta\sigma_\alpha$)
4. Change in subgrain size (e.g. relaxation process during thermomechanical treatment), ($\Delta\sigma_{SG}$)

The micromechanical model:

$$\Delta R_p = \Delta\sigma_G + \Delta\sigma_h + \Delta\sigma_\alpha + \Delta\sigma_{SG}$$

Effect of microstructure on properties

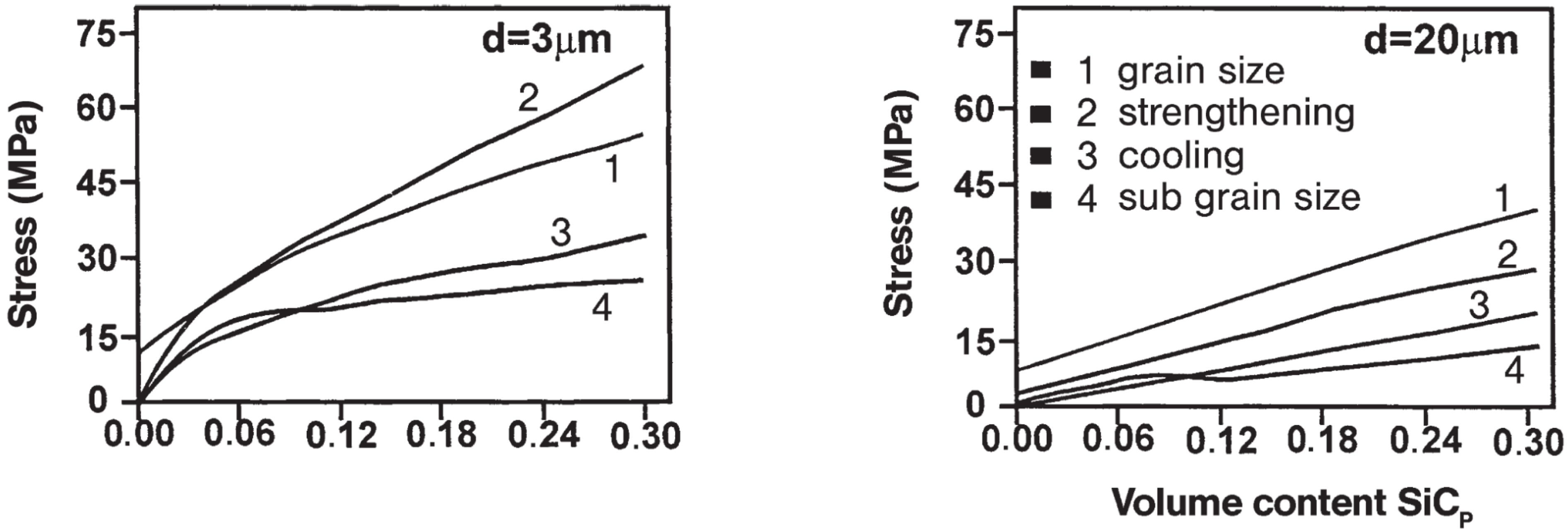
$$\Delta R_p = \Delta\sigma_G + \Delta\sigma_h + \Delta\sigma_\alpha + \Delta\sigma_{SG}$$

- $\Delta\sigma_G = k_1 * \frac{1}{\sqrt{D_G}},\ D_G = d * \left(\frac{1-f_P}{f_P}\right)^{1/3}$
- $\Delta\sigma_h = K * G * f_P * \left(\frac{2b}{d}\right)^{1/2} * \varepsilon^{1/2}$
- $\Delta\sigma_\alpha = \alpha * G * b * \rho^{1/2}, \qquad \rho = 12 * \Delta T * \frac{\Delta C * f_P}{bd}$
- $\Delta\sigma_{SG} = k_2 * \frac{1}{\sqrt{D_{SG}}}$

Where ΔR_p is the reinforcing effect, α, k_1, k_2, K are constants, D_G is the resulting grains size, D_{SG} is the resulting subgrain size, d is the particles size, b is the burger's vector, G is the shear modulus, ε is the strain, ΔT is the temperature difference, ΔC is the difference in thermal expansion coefficient between the matrix and particle

Effect of microstructure on properties

$$\Delta R_p = \Delta\sigma_G + \Delta\sigma_h + \Delta\sigma_\alpha + \Delta\sigma_{SG}$$



The contributions of different mechanisms (especially strain hardening increase) change as particle size decreases

Effect of microstructure on properties

The model equations used to estimate the Young's moduli of long fiber reinforced composites can be applied to short fibers and particles by modification of the equations:

- Linear rule of mixture

$$E_C = f_F * E_f + f_M * E_M$$

- Inverse mixture rule

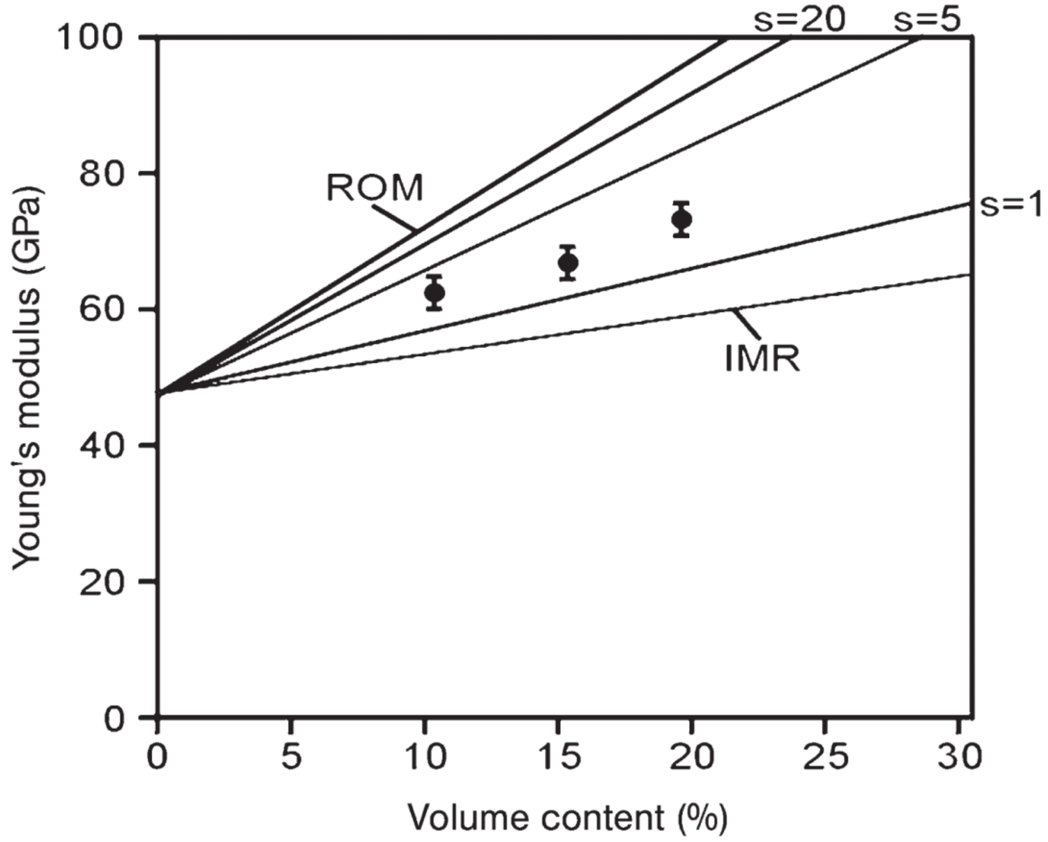
$$E_C = \frac{E_F * E_M}{f_F * E_M + f_M * E_F}$$

An effective geometry factor is added which can be determined from the structure of the composite materials as a function of the load direction

$$E_C = \frac{E_M * (1 + 2 * f_P * S * q)}{1 - f_P * q}, \qquad q = \frac{\left(E_f/E_M\right) - 1}{\left(E_f/E_M\right) + 2S}$$

Where S is the geometry factor of the fiber or particle

Effect of microstructure on properties



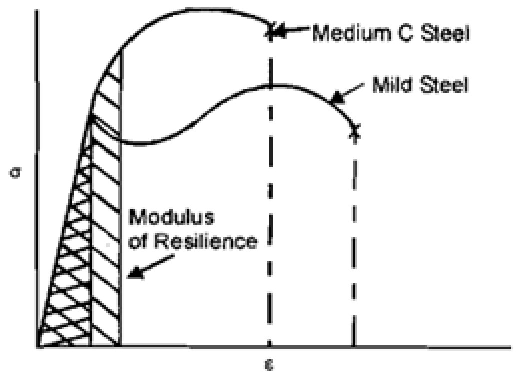
Data for SiC particle reinforced magnesium

Effect of microstructure on properties

- Example

Toughening mechanisms

The area under the stress-strain curve gives us toughness



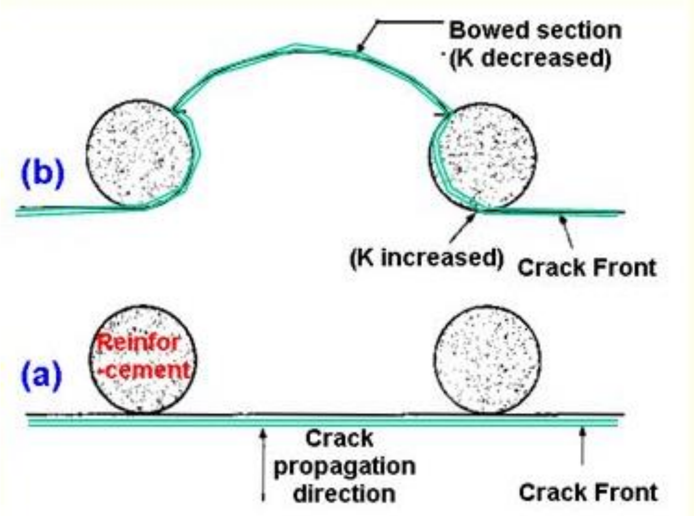
If both areas are the same, the one with the higher strength is tougher to fracture

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

Crack bowing



Crack bowing toughening mechanism (a) crack approaches (b) crack bowed at reinforcement

Fibers result in non-linear crack front

Toughness increases with fiber volume fraction and aspect ratio

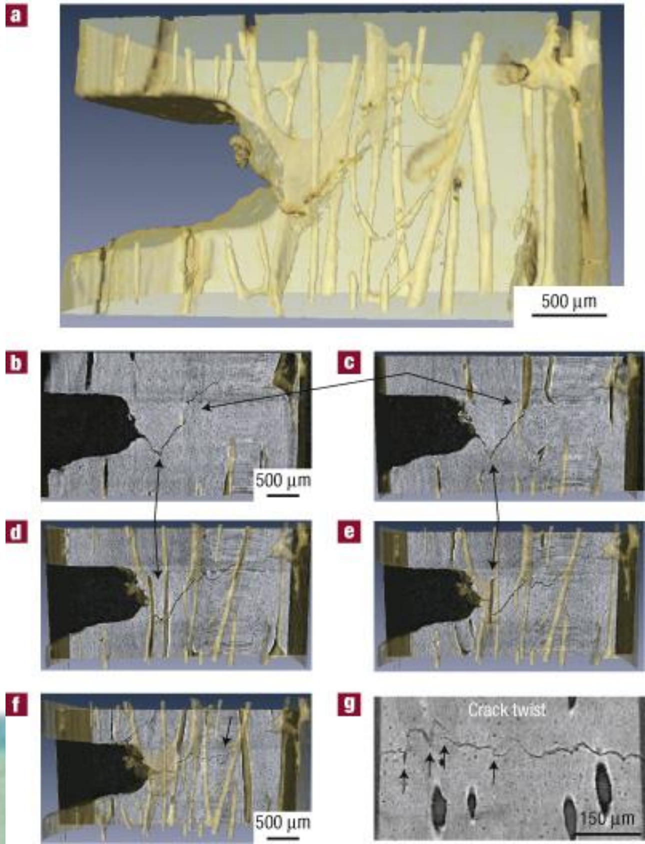
The crack will move around the fiber until stress intensity factor increases at high loads and the fiber fractures

Toughening mechanisms

Crack deflection

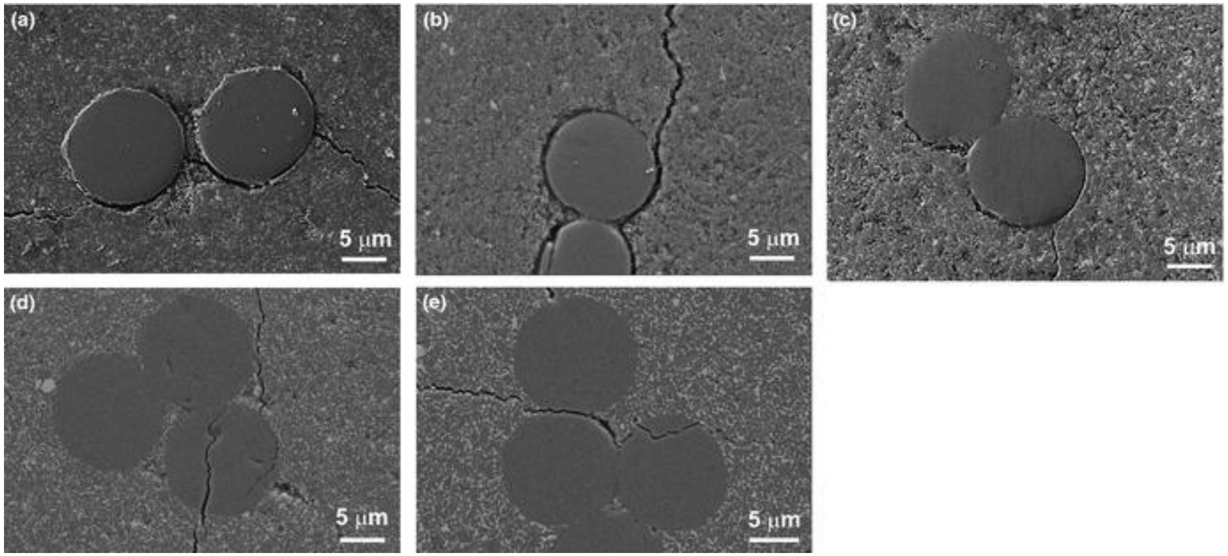
Cracks are deflected from growth plane around fibers due to differences in thermal expansion coefficient and modulus between the fiber and the matrix

Similar mechanism to crack bowing but more effective



Toughening mechanisms

Debonding



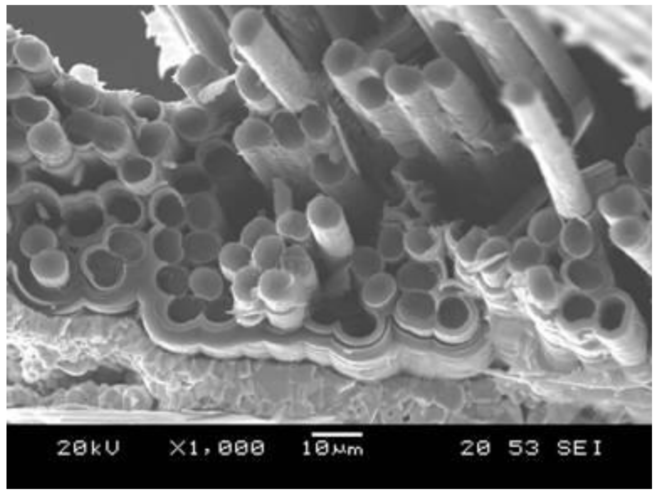
Cracks induce creation of new surfaces between the fiber and matrix

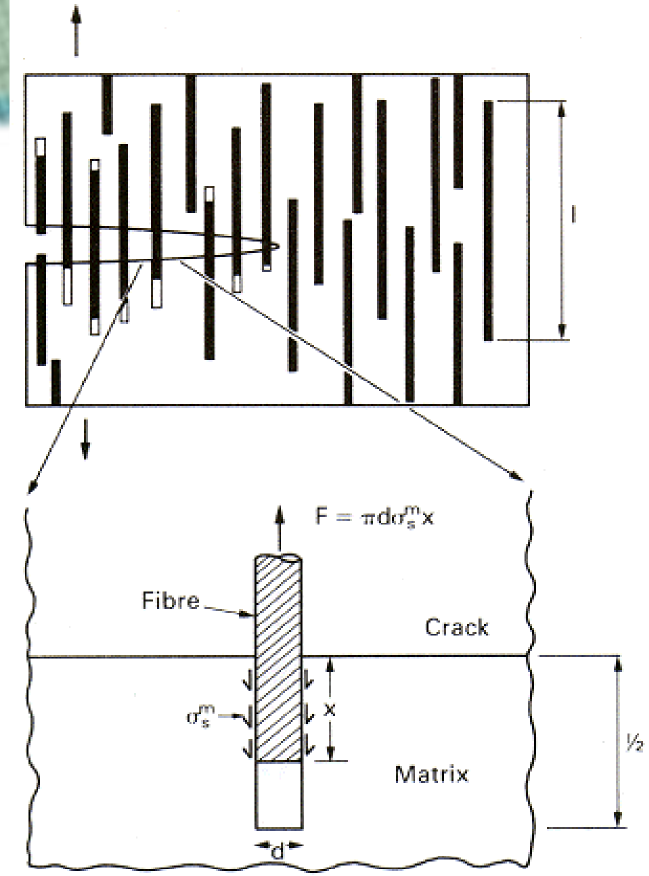
The energy needed to create the surfaces is supplied by the crack and its propagation rate decreases

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

Toughening mechanisms

Fiber oull-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

- Pullout work per fiber $WP = \frac{\pi * d^2 * \sigma_f * l_{cr}}{16}$
- Always ${}^{WP}/_{WD} = \frac{3 * E_f}{\sigma_f} > 1$

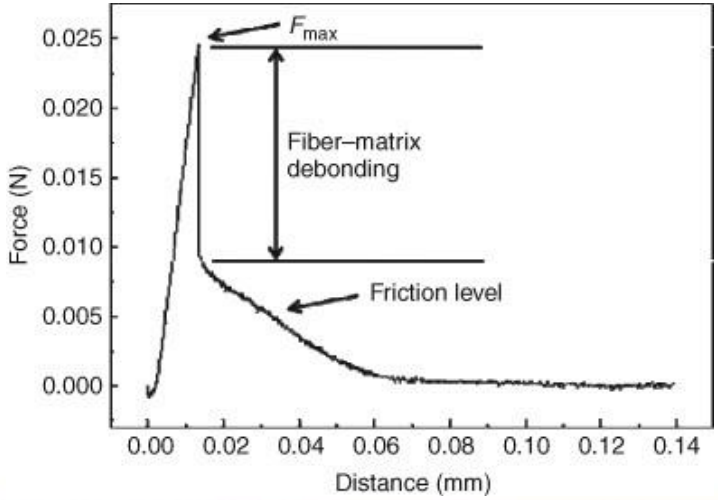
Toughening mechanisms

Fiber oull-out

Only short fibers can be pulled out

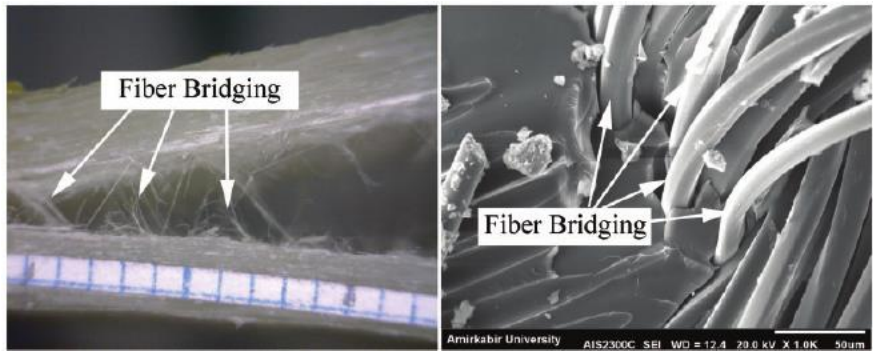
Continuous fibers fracture after debonding (extra energy absorption). Fractured long fibers can be pulled out then

Hence long fibers are more effective in increasing toughness



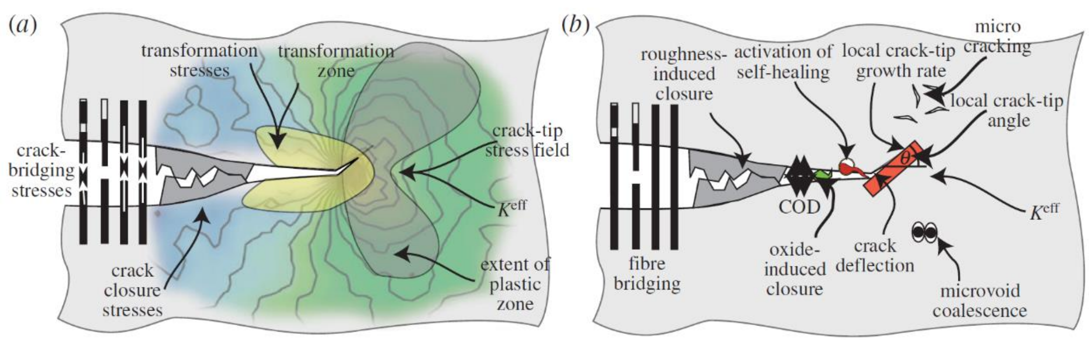
Toughening mechanisms

Fiber bridging



Strong fibers carry load after crack debonding

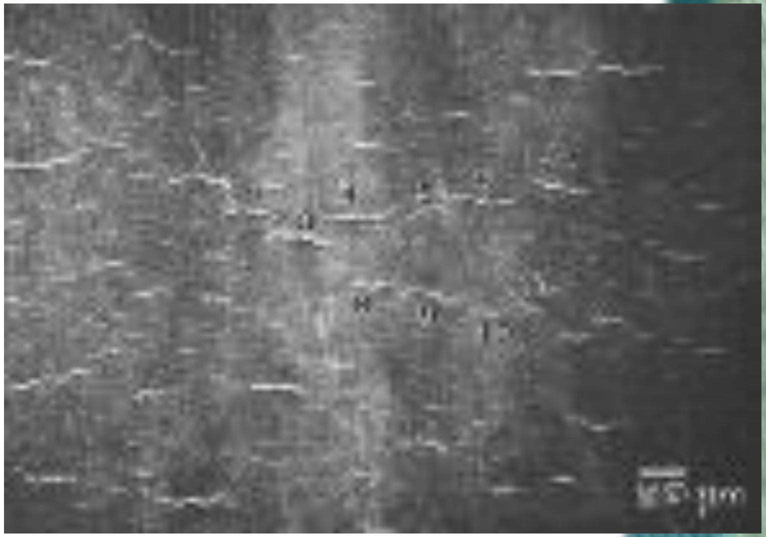
Particulate bridging is called crack wake toughening



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

Toughening mechanisms

Microcracking



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

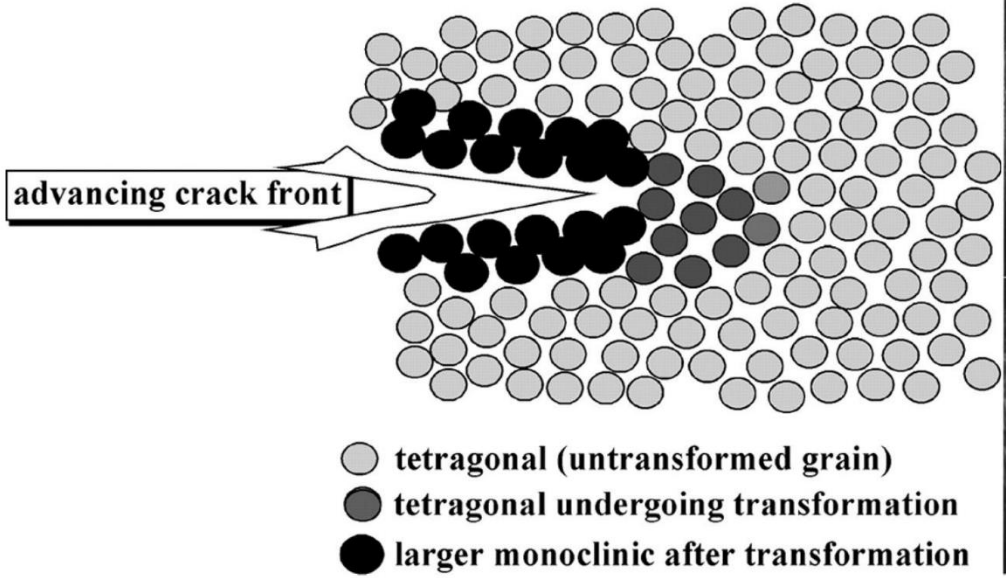
These do not occur in PMCs and MMCs because small amount of deformation or annealing absorb thermal stresses in these materials

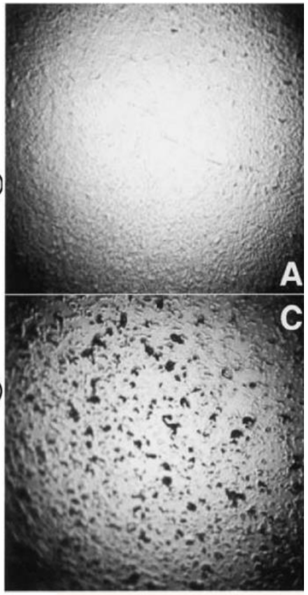
Microcracks in CMCs cause branching, blunting or deflection of macrocracks

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

Toughening mechanisms

Transformation toughening





Phase transformation due to stress occur in some ceramic materials (tetragonal zirconia)

The energy needed for the transformation is absorbed from the main crack