Liquid-State Processes

- **In Situ composites**

✓ Reinforcements are formed during the solidification of the molten metal within the matrix, e.g., controlled unidirectional solidification of eutectic alloys.

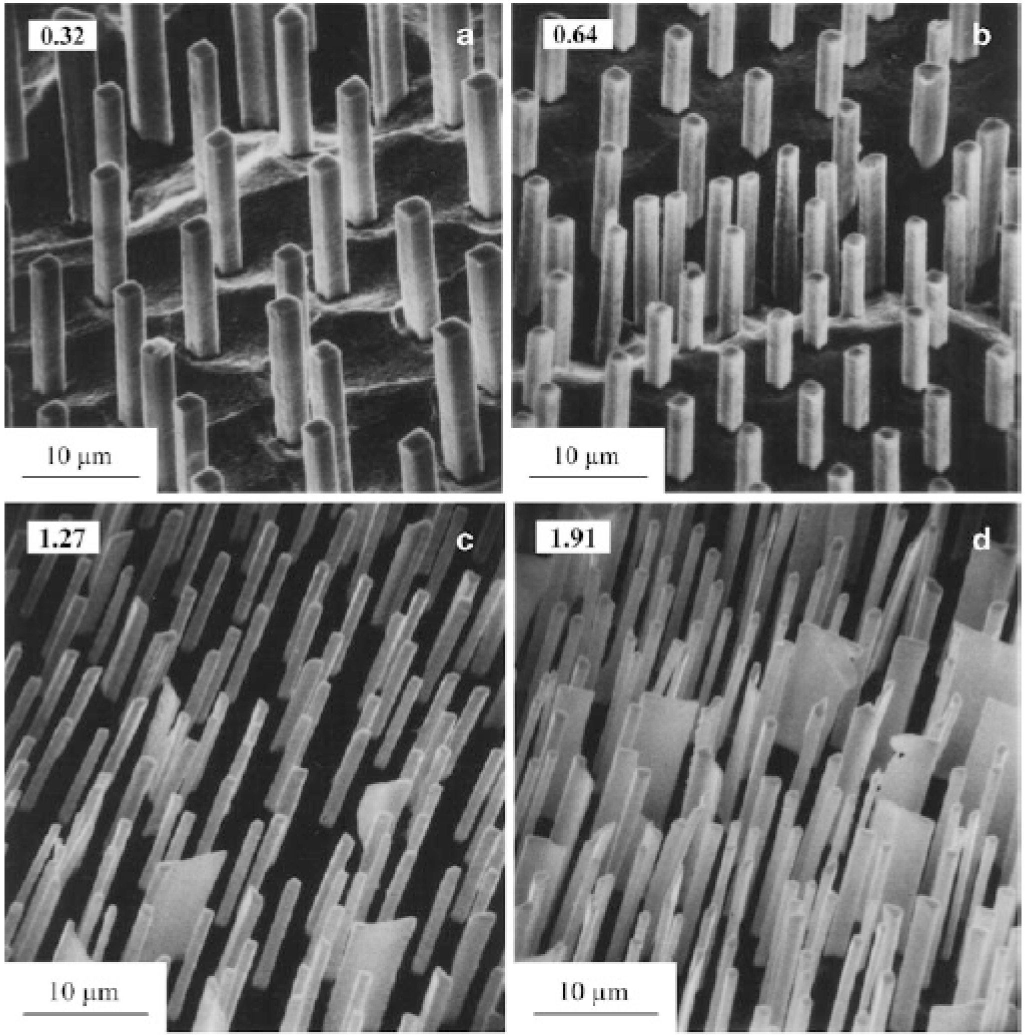


Fig. 6.9 Transverse sections of in situ composites obtained from a eutectic at different solidification rates indicated in *left-hand top* corners (cm/h). The nickel alloy matrix has been etched away to reveal the TaC fibers. [From Walter (1982), used with permission]

Solid-State Processes

Some of the more important processes:

✓ **Diffusion bonding**

- Used to join similar or dissimilar metals

- Predetermined stacking of:

  ✓Matrix alloy foil and fiber arrays

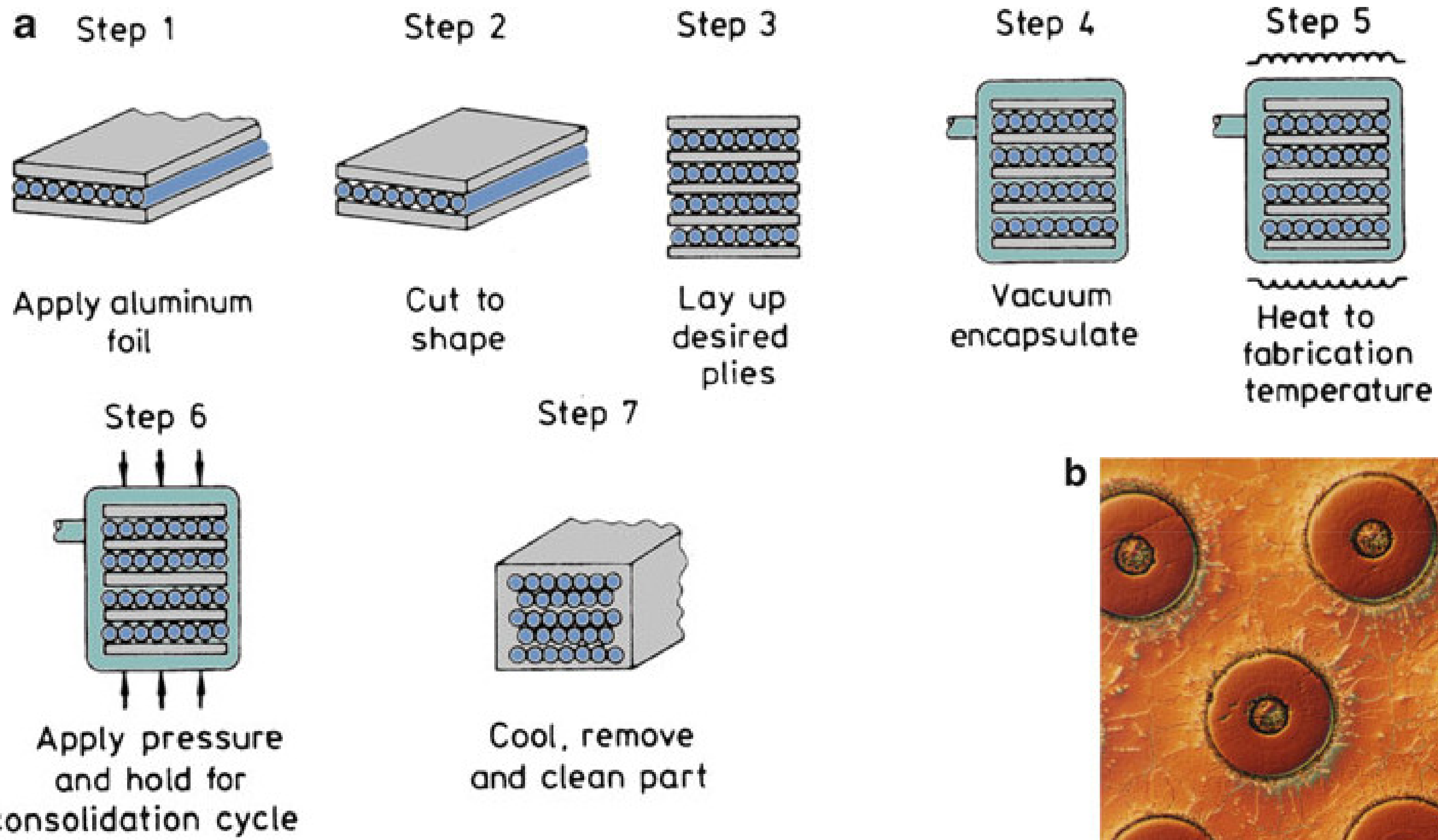
  ✓Composite wire

  ✓Monolayer laminates

- Simultaneous application of pressure and high temperature

  → Inter-diffusion of atoms from clean metal surfaces in contact at elevated temperature

Solid-State Processes



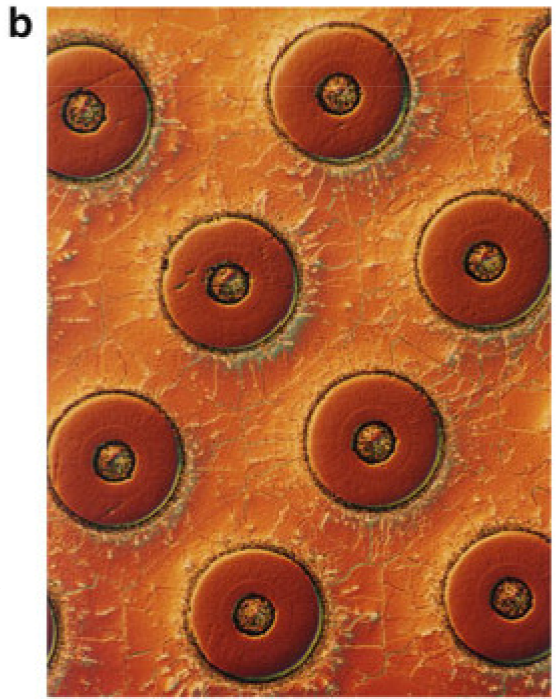


Fig. 6.8 (a) Schematic of diffusion bonding process.

(b) Microstructure of Ti/SiC$_{fiber}$ composite made by diffusion.
(900°C, 105 MPa, 3 h, fiber diameter =142 μm)

Solid-State Processes

✓ The main advantages:

- The ability to process a wide variety of matrix metals
- Control of fiber orientation and volume fraction

× The main disadvantages:

- Processing times of several hours
- High processing temperatures and pressures
- Quite expensive
- Only objects of limited size can be produced

Solid-State Processes

✓ **Deformation processing of metal/metal composites**

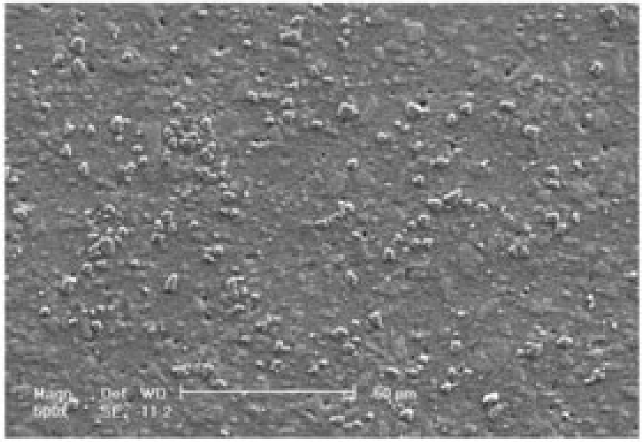
•**Less conventional: In-situ composite**

- Extrusion, drawing, rolling or … of a ductile two-phase material.
- The two phases co-deform → the minor phase elongates and becomes fibrous within the matrix
- The starting material is usually a billet prepared by casting or powder metallurgy methods.

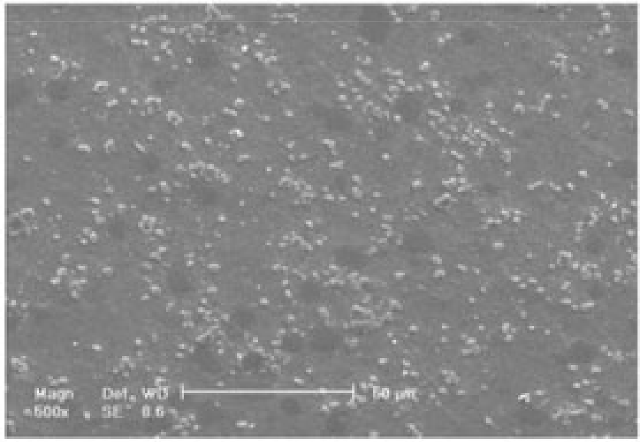
•**More conventional:**

- **Roll bonding** to produce sheet laminated MMCs
- **ARB** (accumulative roll bonding)
- **CAR** (continual annealing and roll-bonding)

ARB



CAR



A356/10 vol.% SiC composites
(10 cycles at room temperature)

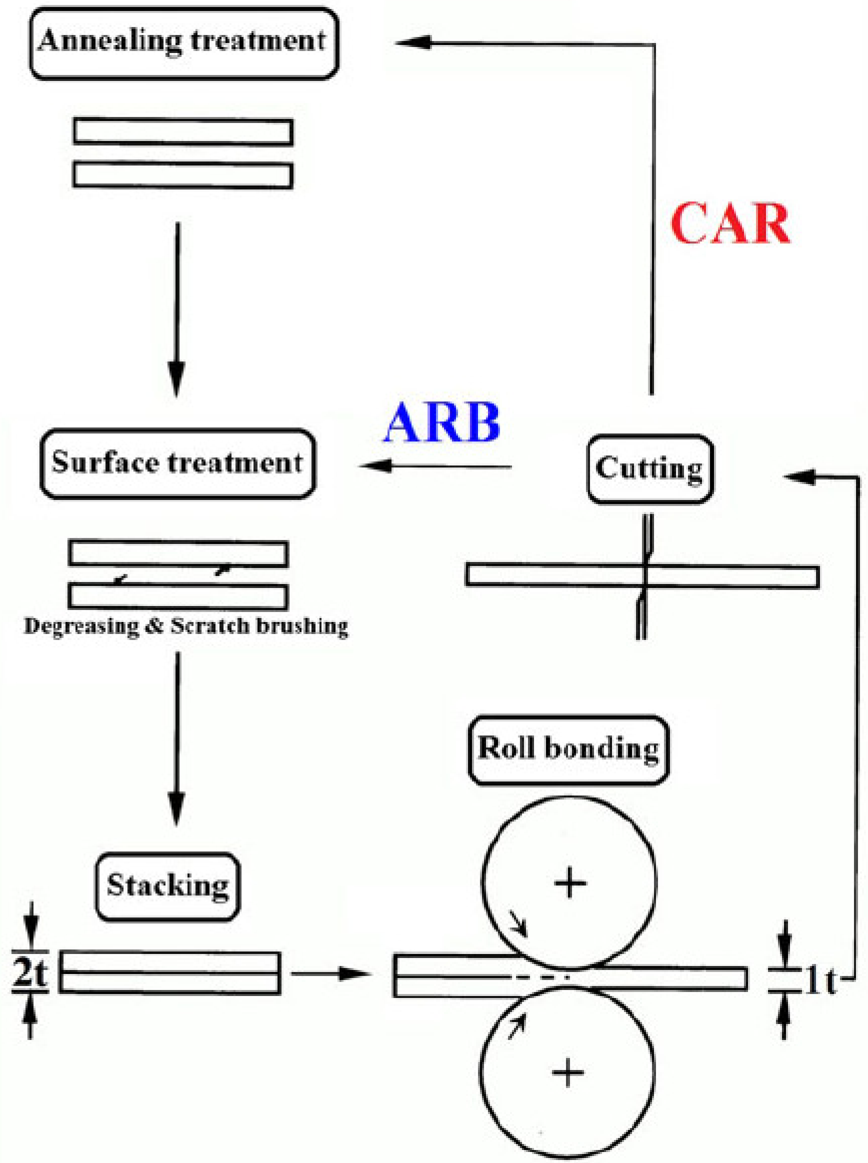


Fig. 2 Schematic illustration of ARB and CAR processes

 R. Jamaati et al., J Mat Eng and Perform 21(7), 2012, 1249-1253.

Solid-State Processes

• ***Nb–Ti composite superconductors***

✓Extremely fine Nb–Ti superconducting filaments embedded in a copper matrix

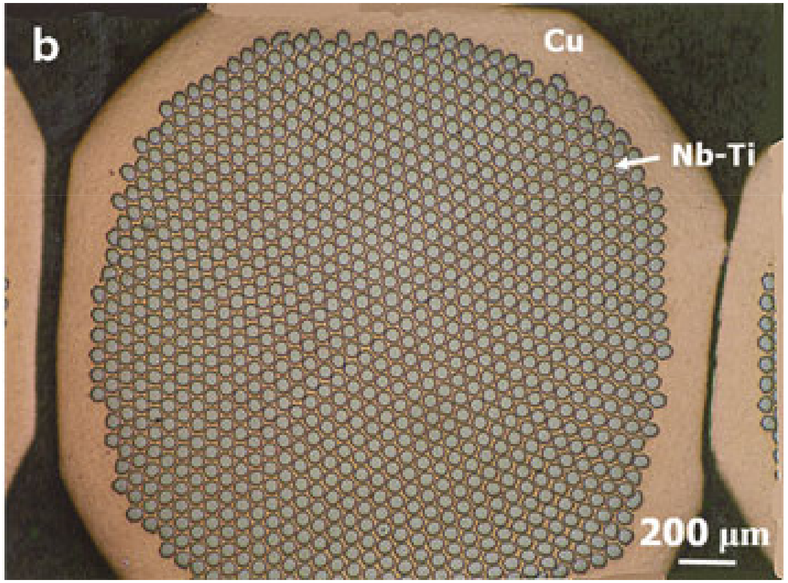


Fig. 9.6 (b) One strand containing 1,060 filaments (Dia. = 50 μm)

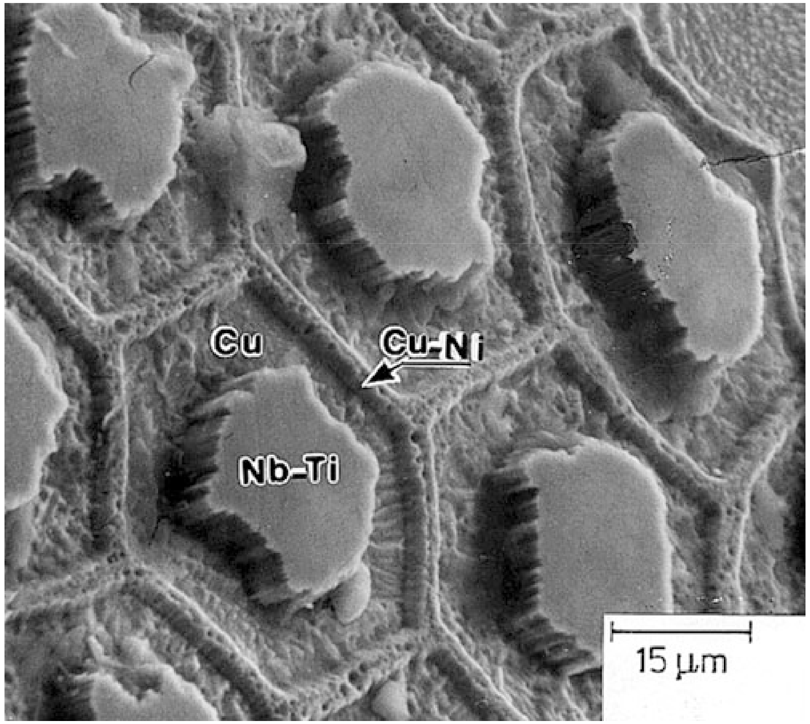


Fig. 9.7 SEM of Cu/Nb-Ti superconductor

Solid-State Processes

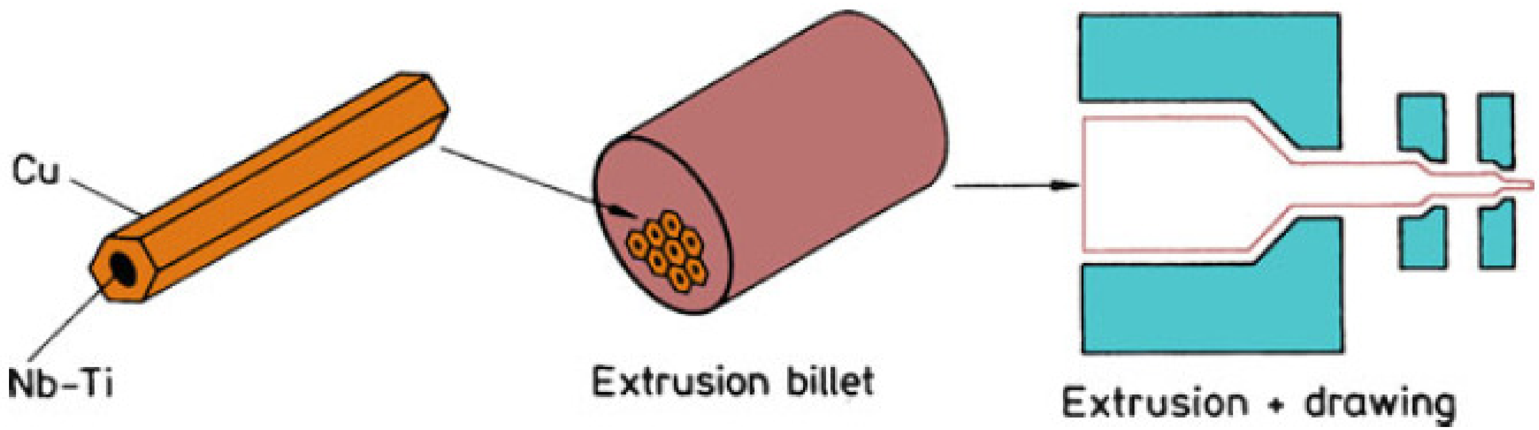


Fig. 9.5 Fabrication route for Nb–Ti/Cu composite superconductors

✓Annealed Nb–Ti rods are inserted into hexagonal-shaped high purity copper tubes.

✓These rods are loaded into a copper tube, evacuated, sealed, and extruded.

✓The extruded rod is cold drawn and annealed repeatedly to the appropriate final size and properties.

Solid-State Processes

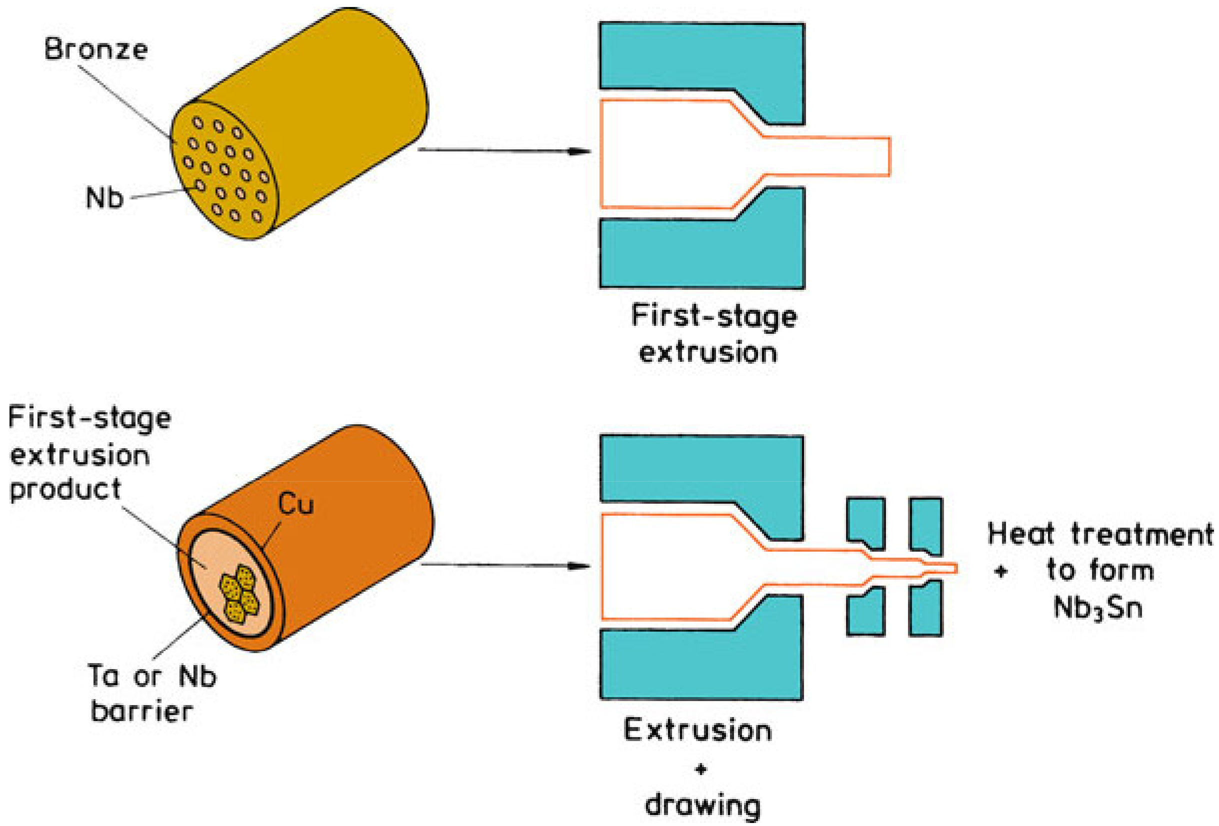


Fig. 9.8 Schematic of the bronze method of fabricating Cu/Nb_3Sn superconductor

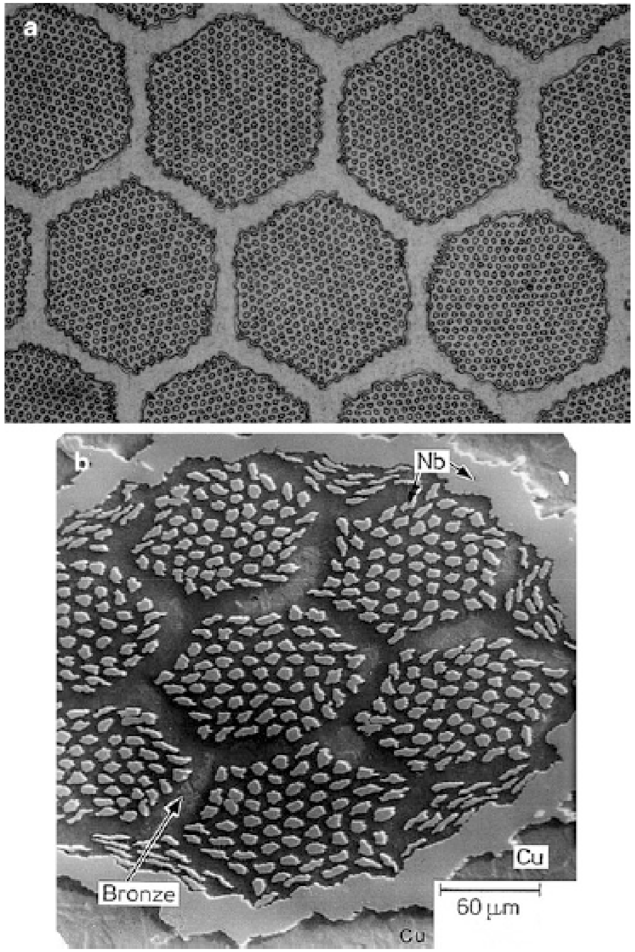


Fig. 9.9 (a) An Nb_3Sn/Cu composite superconductor. Each little dot in the picture is a 4-µm dia. Nb_3Sn filament. (b) SEM of a Nb/bronze composite before the heat treatment to form Nb_3Sn.

Solid-State Processes

- **Deposition techniques for MMC fabrication**

  1- Coating individual fibers in a tow with the matrix material

  2- Diffusion bonding to form a consolidated composite plate or structural shape

•Several deposition techniques are available:

✓Immersion plating

✓Electroplating

✓Spray deposition

✓Chemical vapor deposition (CVD)

✓Physical vapor deposition (PVD)

More information available in the text book.

Mechanical Properties

- **Young's Modulus**

✓ Unidirectionally reinforced continuous fiber reinforced MMCs:
  - A linear increase in the longitudinal Young's modulus as a function of the fiber volume fraction
  - The modulus increase in a direction transverse to the fibers is very low.

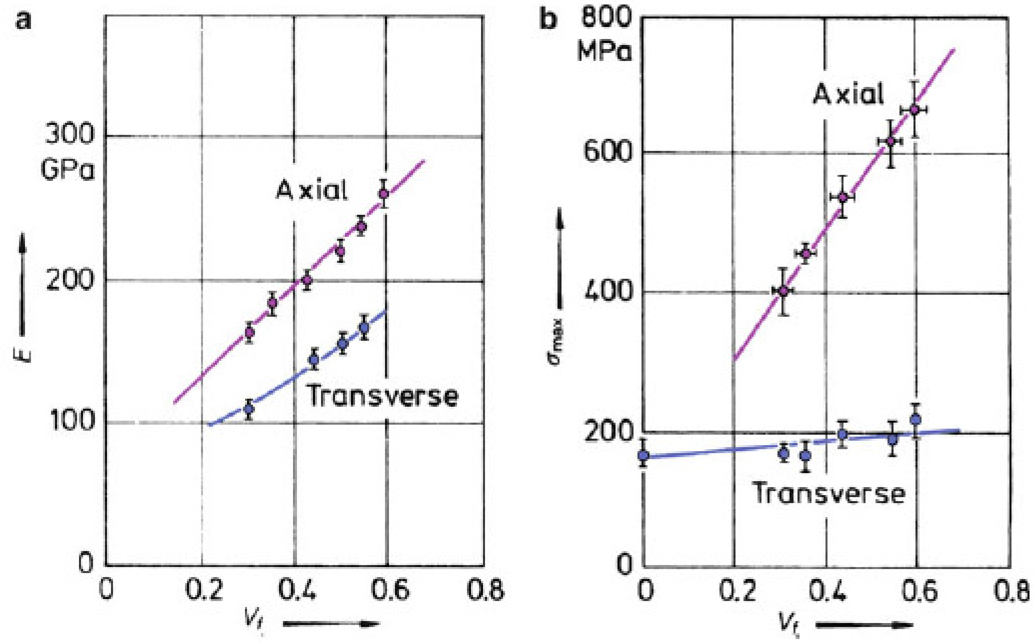


Fig. 6.19 Properties of Al_2O_3/Al–Li composites as a function of fiber volume fraction (V_f): (a) axial and transverse Young's modulus vs. fiber volume fraction, (b) axial and transverse ultimate tensile strength vs. fiber volume fraction. [From Champion et al. (1978), used with permission]

Mechanical Properties

- Particle reinforced MMCs :
  - Increased modulus

  - The stiffness enhancement in particulate composites is reasonably isotropic

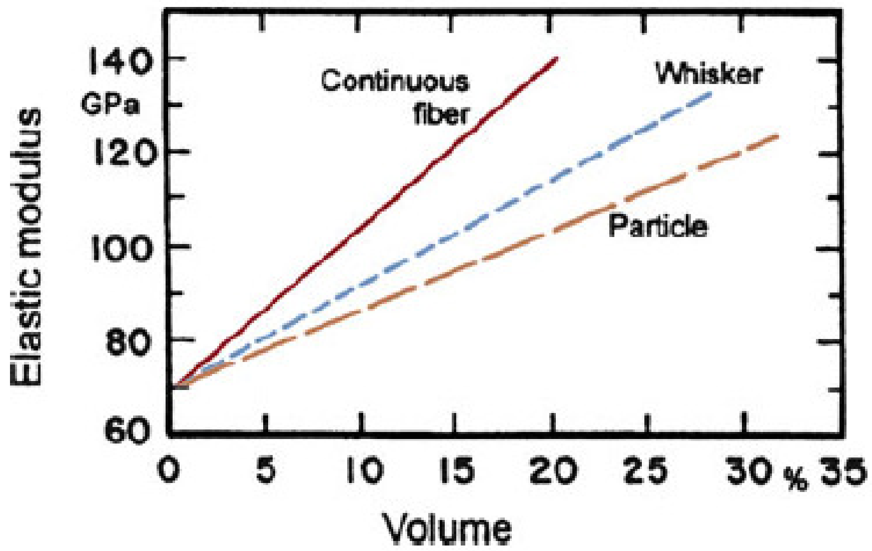


Fig. 6.20 Increase in Young's modulus of an MMC as a function of reinforcement volume fraction for continuous fiber, whisker, or particle reinforcement

Properties

- **Strengthening mechanisms in metal matrix composites**

- **1- Direct strengthening:**
  - – Considers only the contribution of the reinforcement and the matrix (load transfer from the matrix to high modulus reinforcements)
  - – Is critically dependant on the reinforcement-matrix interface
  - – Does not take into account any strength contribution from microstructural changes in the metal matrix

- For fiber reinforced MMCs:
  - – Rule of mixtures: $\sigma_c = \sigma_f V_f + \sigma_m V_m$
    - σ = the stress
    - V = the volume fraction
    - c, f, and m denote the composite, fiber, and matrix, respectively

➢Strengthening mechanisms in metal matrix composites

• For particle reinforced MMCs:

$$\Delta\sigma_l = v_p\sigma_m\left[\frac{(l+t)A}{4l}\right]$$

$\Delta\sigma_l$ = load-bearing contribution of reinforcement
v_p = volume fraction of particles in the matrix
σ_m = yield strength of the matrix
l = size of the particulate parallel to the load direction
t = thickness of the particulate, and
A = l/t = particles aspect ratio

•For equiaxed (spherical) particles:

$$\Delta\sigma_l = 0.5v_p\sigma_m$$

A. Sanaty-Zadeh, P.K. Rohatgi, Materials Science and Engineering A 531 (2012) 112– 118.

➢Strengthening mechanisms in metal matrix composites

➢ **2- Indirect strengthening:**

– The reinforcement-induced changes in matrix microstructure and properties including:

- Orowan strengthening
- Grain and substructure strengthening
- Quench hardening
- Work hardening
- Solid solution strengthening

- The indirect strengthening appears to be more important in particle reinforced composites.

➢Strengthening mechanisms in metal matrix composites

➢ I- Orowan strengthening

- Hard and non-shearable particles may pin and block the dislocations.
- Orowan effect=Gb/l
  - G = shear modulus of the matrix
  - b = Burgers vector of the matrix
  - l= particle spacing
- The degree of strengthening is believed to be insignificant for micro-sized reinforcements.
- Nano MMCs seem to benefit more from this mechanism.

➢Strengthening mechanisms in metal matrix composites

➢ II- Grain and substructure strengthening

- Hall–Petch relationship:

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}}$$

- σ_y = yield strength
- σ_0 = a materials constant (resistance of the lattice to dislocation motion)
- k_y = the strengthening constant
- d = grain or sub-grain size in the matrix.

- Grain boundary strengthening can be high in spray cast and powder metallurgy processed composites.

➢Strengthening mechanisms in metal matrix composites

A356-2%CNT

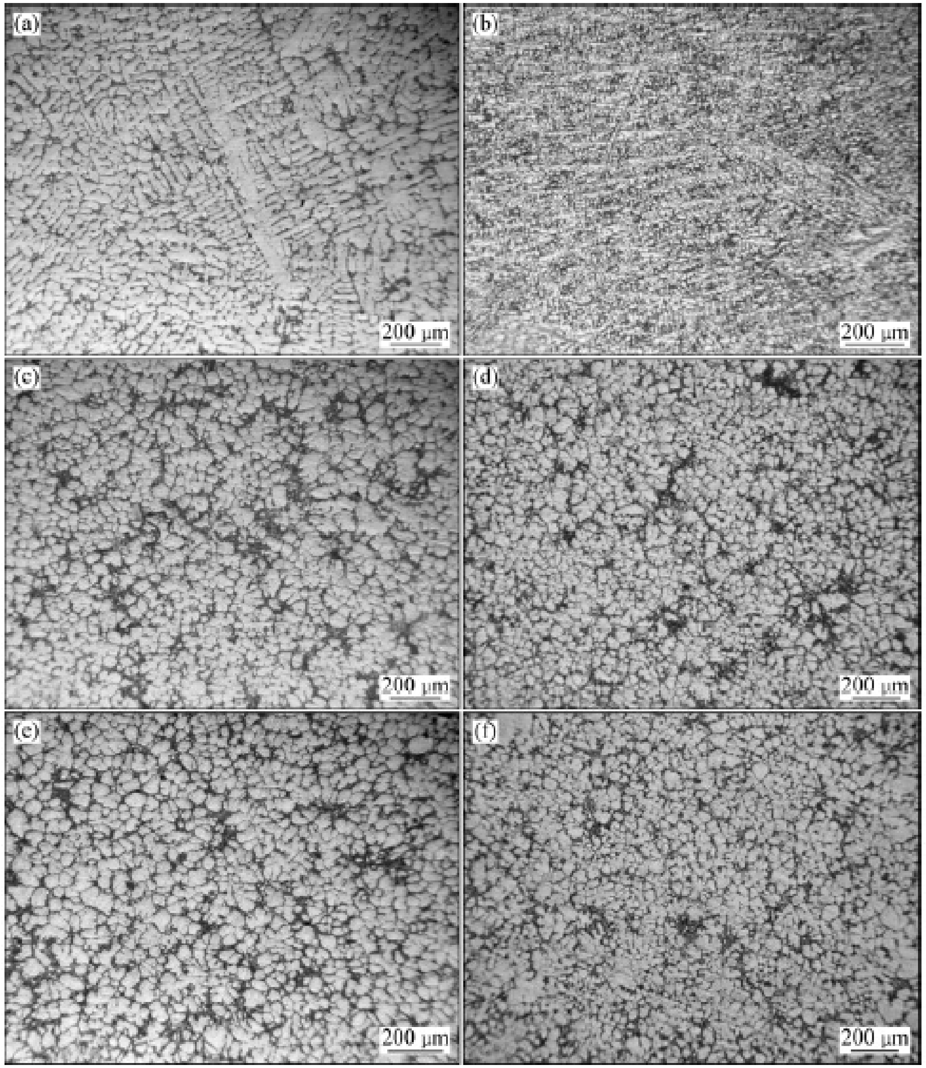


Fig.5 Typical micrographs of cast samples: (a) A-0-0; (b) A-0-2; (c) A-15-0; (d) A-15-2; (e) A-30-0; (f) A-30-2

Abasipour, B., Niroumand, B., Monir-Vaghefi, M., Transactions of Nonferrous Metals Society of China, 20, (2010) 1561-1566.

➢Strengthening mechanisms in metal matrix composites

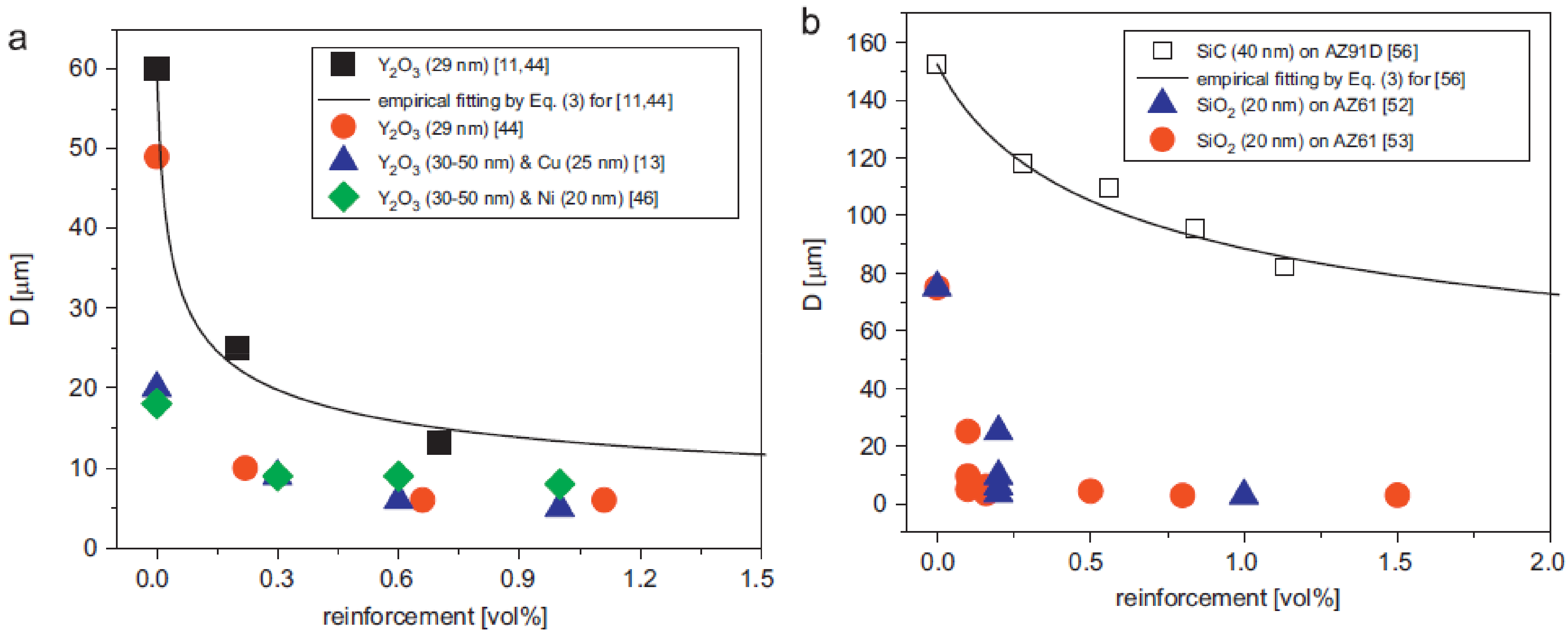


Fig. 3. Influence of reinforcement particle vol% on the matrix grain size refinement of Mg MMNCs, (a) influence of Y_2O_3 on pure Mg MMNCs, and (b) influences of SiO_2 and SiC on alloy Mg MMNCs.

J.B. Ferguson, F. Sheykh-Jaberi, C.S. Kim, P.K.Rohatgi, K. Cho, Materials Science & Engineering A, 558 (2012) 193–204.

➢Strengthening mechanisms in metal matrix composites

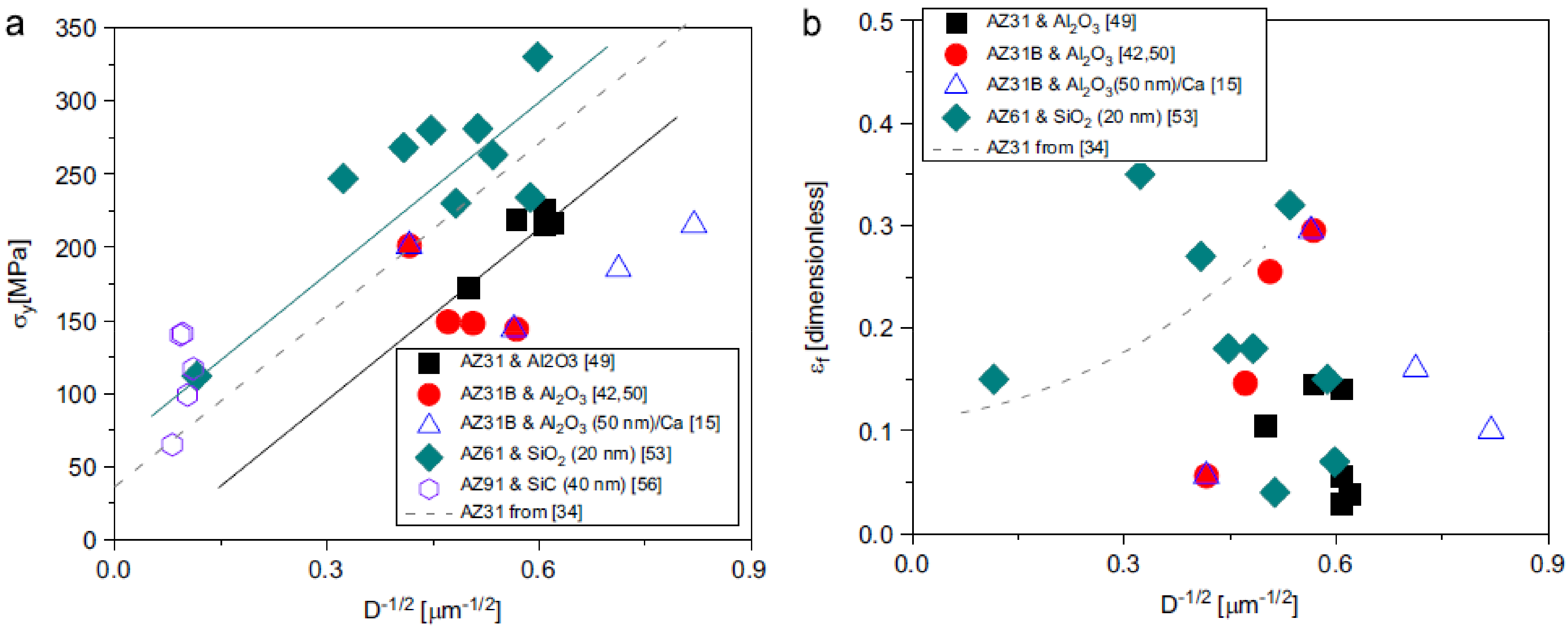


Fig. 7. Influence of Al_2O_3, SiO_2, and SiC concentrations and inverse square root of grain size on the (a) yield strength (σ_y) and (b) strain to failure (ε_f) of Mg alloy MMNCs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

J.B. Ferguson, F. Sheykh-Jaberi, C.S. Kim, P.K.Rohatgi, K. Cho, Materials Science & Engineering A, 558 (2012) 193–204.

➢Strengthening mechanisms in metal matrix composites

➢ **III- Quench hardening** .

- Reinforcements normally have smaller coefficient of thermal expansions (CTEs) than the matrix

- When subjected to a temperature change, thermal stresses are generated in both of the components

- A metal matrix undergoes plastic deformation in response to the thermal stresses generated and thus alleviates them

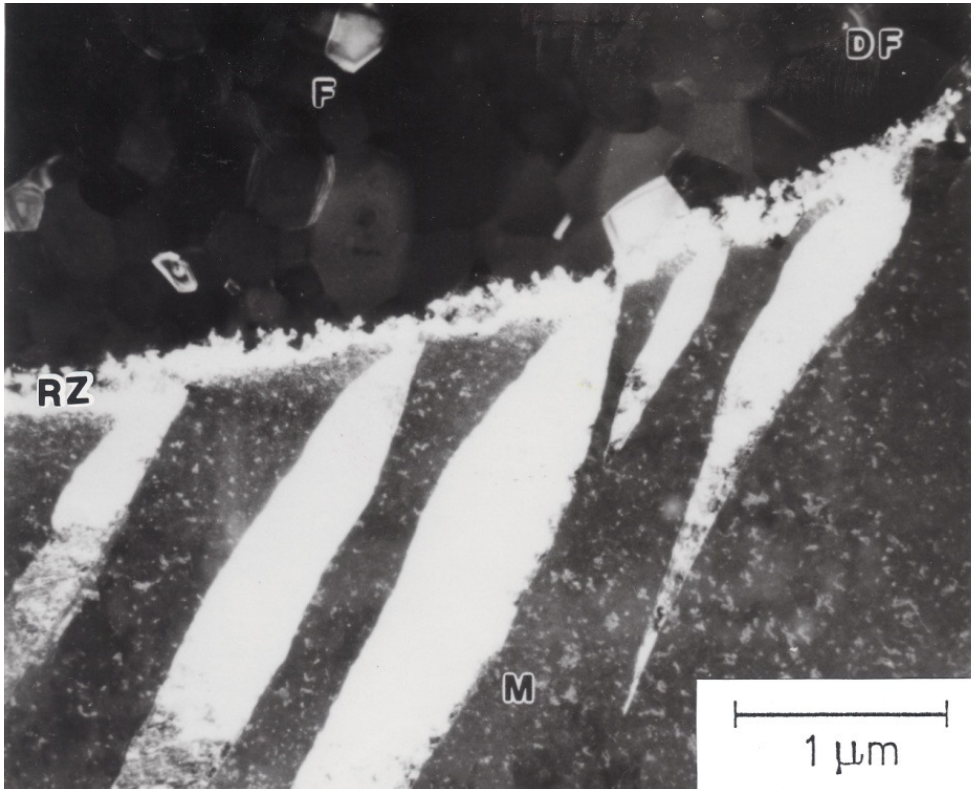
- A high density of dislocations may be generated around the reinforcements

➢Strengthening mechanisms in metal matrix composites

Alumina fiber/Mg alloy matrix

Twins in Mg matrix →
plastic deformation in Mg
due to thermal stresses

RZ= reaction zone



➢Strengthening mechanisms in metal matrix composites

•A dislocation etch-pitting technique was used to delineate dislocations in single crystal copper matrix (1975).

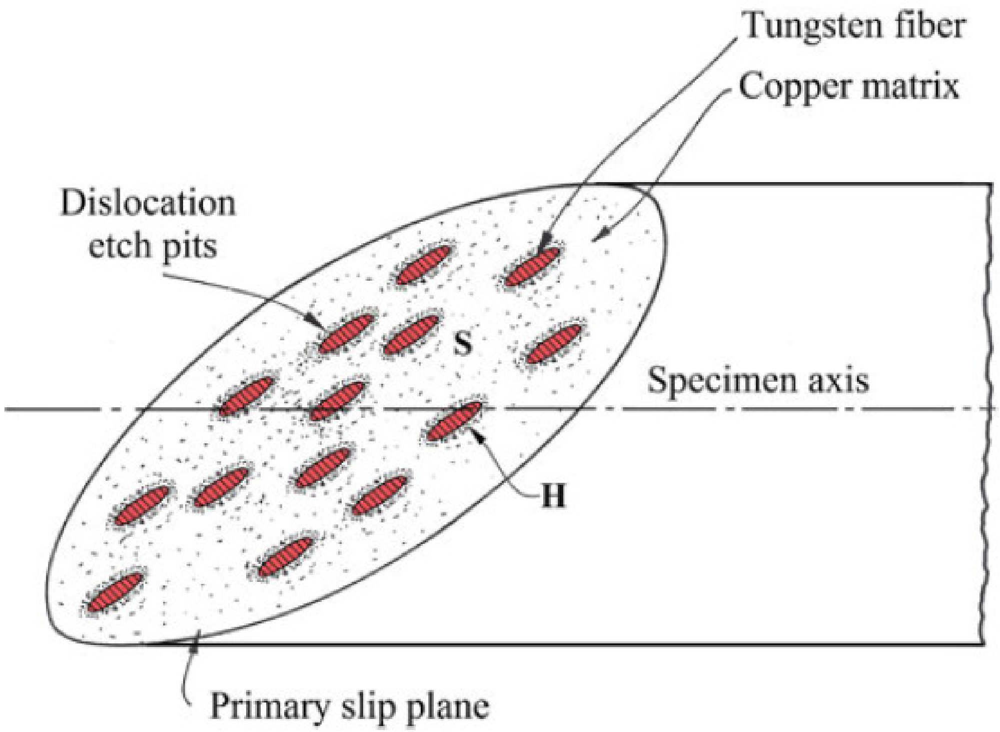


Fig. 6.16 A primary plane section of a metal matrix composite is shown as having a hard zone (high dislocation density) around each fiber and a soft zone (low dislocation density) away from the fiber

➢Strengthening mechanisms in metal matrix composites

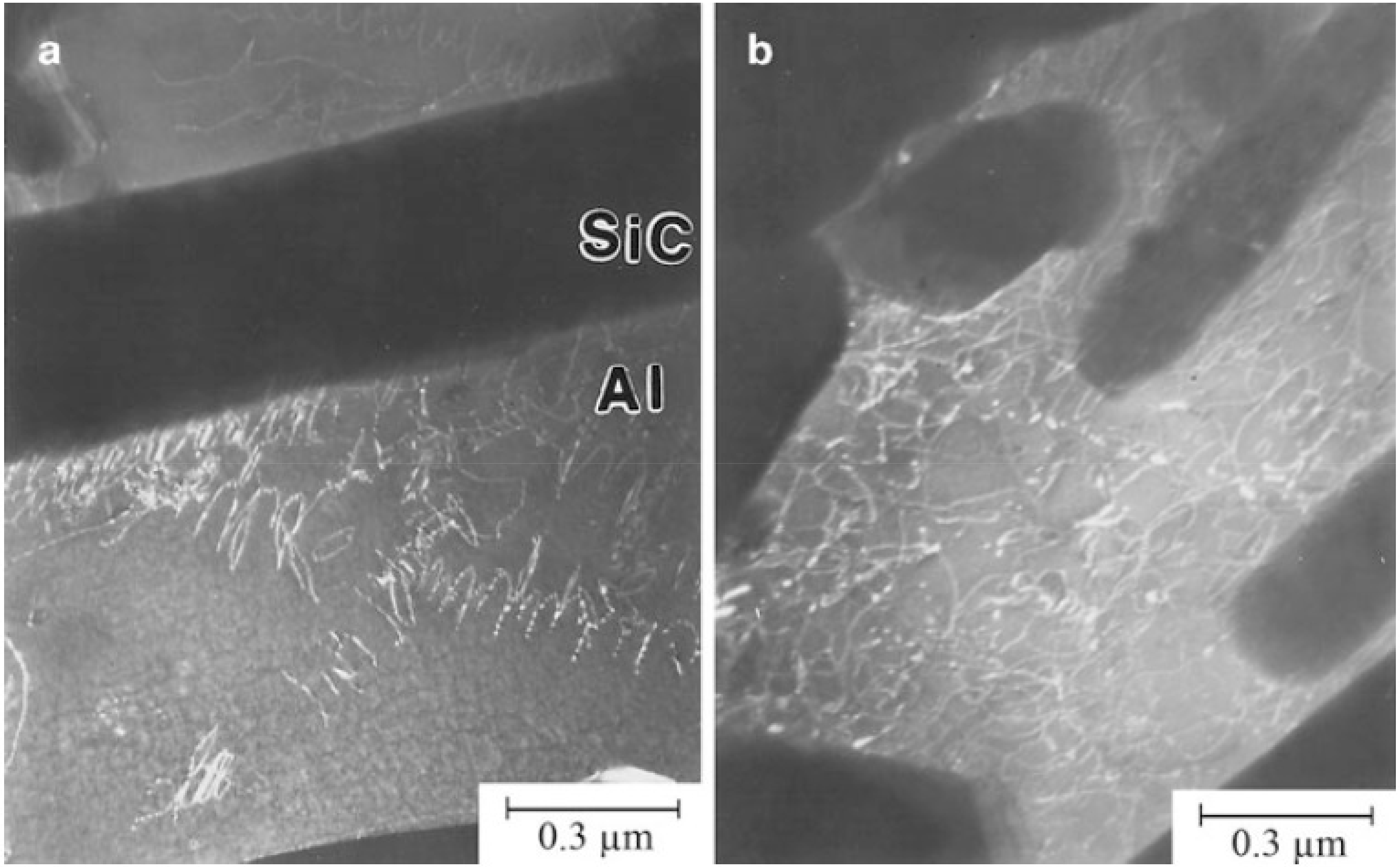


Fig. 6.26 Dislocation distribution in the aluminum matrix of a SiC_w/Al composite: (**a**) inhomogeneous dislocation distribution before testing, (**b**) uniform dislocation distribution after fatigue testing. [From Williams and Fine (1985a), used with permission]

➢Strengthening mechanisms in metal matrix composites

- Thermal strain in the matrix: $e_m = \Delta\alpha\Delta T$

– The dislocation density resulting from CTE mismatch:

$$\rho_{CTE} = (AeV_p)/b(1 - V_p)d$$

  – A = a geometric constant
  – e = the thermal misfit strain
  – b = the Burgers vector
  – V_p = the particle volume fraction
  – d = the particle diameter

- The strength contribution is given by

$$\sigma_q = \alpha Gb(\rho_{CTE})^{1/2}$$

α = a constant

G = the shear modulus of the matrix

➢Strengthening mechanisms in metal matrix composites

- Accelerated aging processes due to heterogeneous nucleation at dislocations

- This contribution of quench hardening to strength can be significant.

➢Strengthening mechanisms in metal matrix composites

➢ IV- Work hardening .

- Due to the modulus mismatch (strain misfit) between the elastic reinforcement and the plastic matrix

- Reinforcements affect the matrix work hardening rate.

✓ **Effect of modulus mismatch on the strength of a composite**

$$\sigma_d = \sqrt{3}\alpha G b \sqrt{\rho^{\mathrm{EM}}}$$

- α = a constant (~0.5)
- ρ^{EM} = the dislocation density caused by modulus mismatch
- G = the shear modulus of the matrix
- b = the Burger's vector

$$\rho^{\mathrm{EM}} = \frac{6v_p}{\pi d_p^3}\varepsilon$$

- v_p= volume fraction of particles
- d_p = the particle diameter
- ε= the uniform deformation

A. Sanaty-Zadeh, P.K. Rohatgi, Materials Science and Engineering A 531 (2012) 112– 118.

➢Strengthening mechanisms in metal matrix composites

➢ **V- Solid solution strengthening**

- The reinforcements may affect the microsegregation as a result of solute segregation at the interfaces or chemical reaction with the matrix.

→ The content and distribution of solute in the matrix is changed

➢Strengthening mechanisms in metal matrix composites

- In MMCs reinforced with continuous fibers, direct strengthening is a major factor.
- For discontinuously reinforced metals, quench hardening and work hardening are likely to be the most active mechanisms.
- For nano-sized reinforcements, Orowan strengthening may become a key mechanism.
- Normal matrix strengthening due to solution and precipitation hardening and grain refinement will give additional strength to the composite.

+ The strength of MMCs is most strongly dependent on the volume fraction of reinforcement.

➢Strengthening mechanisms in metal matrix composites

The overall strength of the composite:

•There are different models. Two examples:

1- Simply add up all the strengthening contributions:

- •Neglects the effect of different mechanisms on each other
- •Assumes that each mechanism behaves independently

$$\sigma = \sigma_0 + \Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3 + \Delta\sigma_4 + \cdots$$

2- Clyne method (for micro composites):

$$\sigma_y = \sigma_0 + \Delta\sigma$$

$$\Delta\sigma = \sqrt{(\Delta\sigma_l)^2 + (\Delta\sigma_{\mathrm{Orawan}})^2 + (\Delta\sigma_{\mathrm{Hall-Petch}})^2 + (\Delta\sigma_{\mathrm{EM}})^2 + (\Delta\sigma_{\mathrm{CTE}})^2 + (\Delta\sigma_{\mathrm{WH}})^2}$$

σ_0 = Yield strength of the unreinforced matrix

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➢Strengthening mechanisms in metal matrix composites

•An expression for the yield strength of a particulate composite:

$$\sigma_{yc} = \sigma_{ym}[1 + (L + t)/4L]V_p + \sigma_{ym}(1 - V_p)$$

σ_{ym} = the yield stress of the unreinforced matrix,

Vp = the particle volume fraction,

L = the length of the particle perpendicular to the applied load and

t = the length of the particle parallel to the loading direction

➢Strengthening mechanisms in metal matrix composites

Mg MMCs reinforced with nano Al_2O_3 particles .

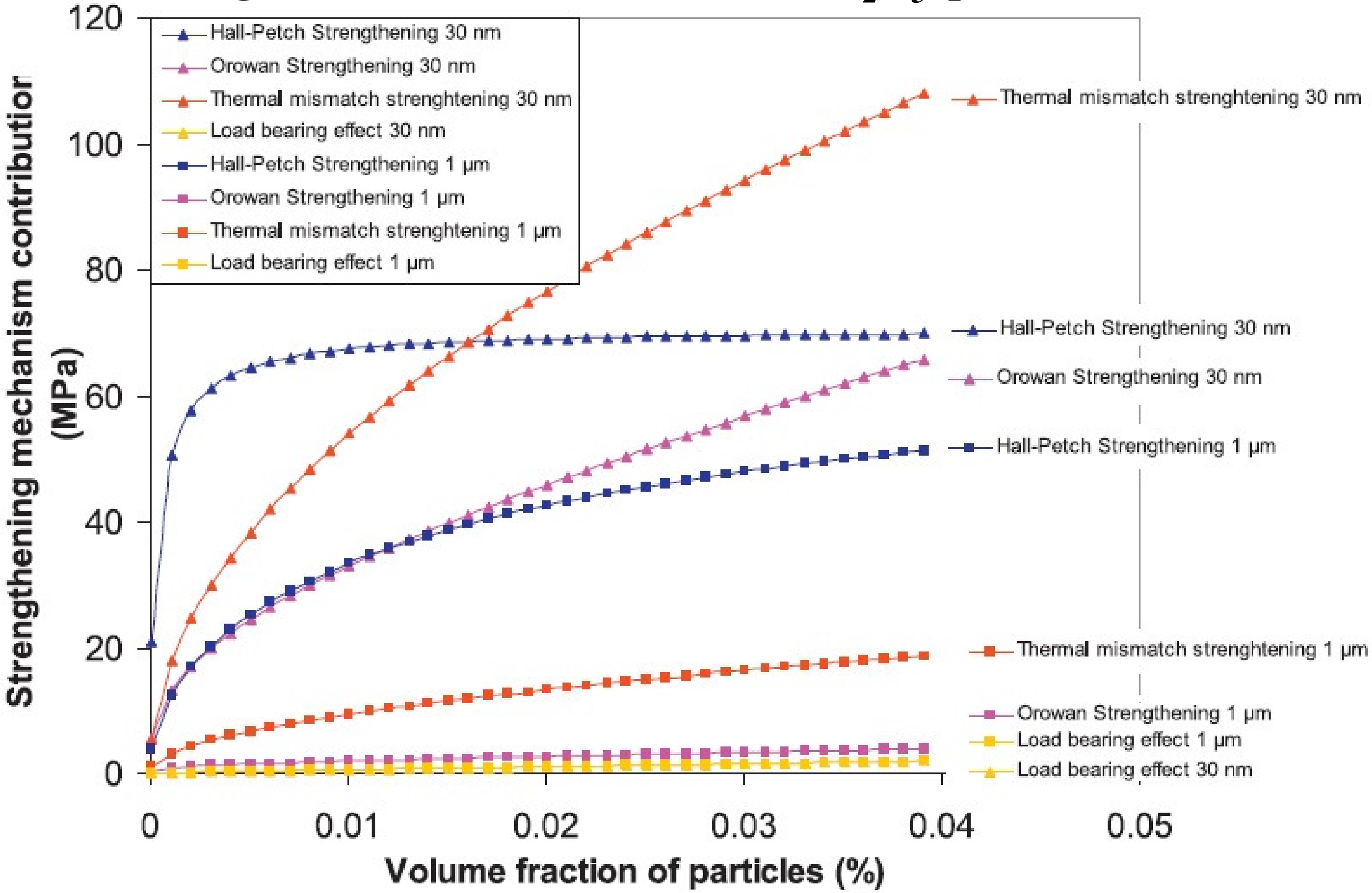

Fig. 7. Strengthening mechanism contributions as a function of volume fraction for the particle sizes 10 nm and 1 μm.

A. Sanaty-Zadeh, P.K. Rohatgi, Materials Science and Engineering A 531 (2012) 112– 118.

➢Strengthening mechanisms in metal matrix composites

- For Mg matrix reinforced with nano-Al_2O_3 and Y_2O_3 particles
  - ✓ There is a 75 nm particle size threshold
  - ✓ Larger particle sizes do not significantly influence the strength of the nanocomposite.

- Theoretical calculation in Prof. Rohatgi's group:
  - ✓ An ideal Al-15vol% Al_2O_3 (10 nm particles)
    - ✓ → **1GPa yield strength!**