CHAPTER 6

Metal Matrix Composites

Metal Matrix Composites

- High specific strength, high specific modulus, good toughness, environmental resistance, higher temperature capabilities

- 1960s: Boron fiber reinforced 6061 aluminum
- 1960s: Unidirectionbally solidified eutectics
- 1970s: Carbon fiber reinforced metallic composites

- Now a variety of reinforcements are availabile, e.g. Al_2O_3, SiC, …

Metal Matrix Composites

- Main activities in MMCs:
  - Boron/Aluminum
  - Carbon/Aluminum
  - Al/Al_2O_3, Mg/Al_2O_3
  - Al/SiC
  - Eutectic or insitu composites
  - Nano composites

Three kinds of metal matrix composites (MMCs):

- Particle reinforced MMCs
- Short fiber or whisker reinforced MMCs
- Continuous fiber or sheet reinforced MMCs

Types of Metal Matrix Composites

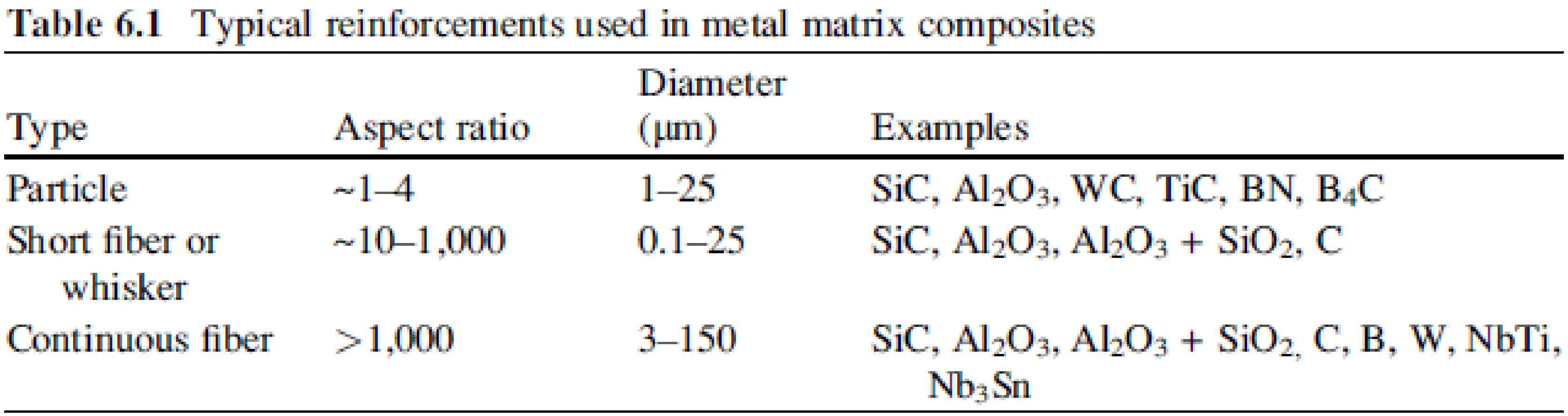


Table 6.1 Typical reinforcements used in metal matrix composites

Type	Aspect ratio	Diameter (μm)	Examples
Particle	~1–4	1–25	SiC, Al_2O_3, WC, TiC, BN, B_4C
Short fiber or whisker	~10–1,000	0.1–25	SiC, Al_2O_3, $Al_2O_3 + SiO_2$, C
Continuous fiber	>1,000	3–150	SiC, Al_2O_3, $Al_2O_3 + SiO_2$, C, B, W, NbTi, Nb_3Sn

- Particle or discontinuously reinforced MMCs have become very important

- Compared to fiber reinforced composites:
  - Inexpensive
  - Relatively isotropic properties

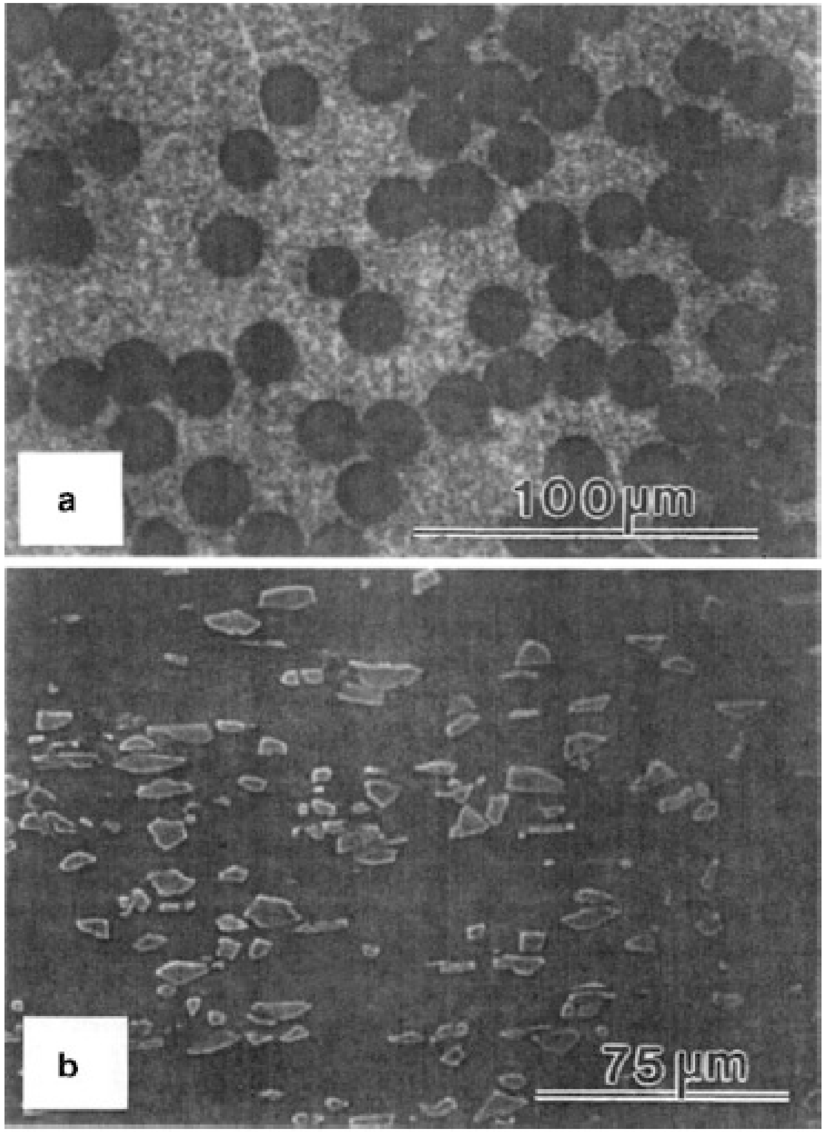
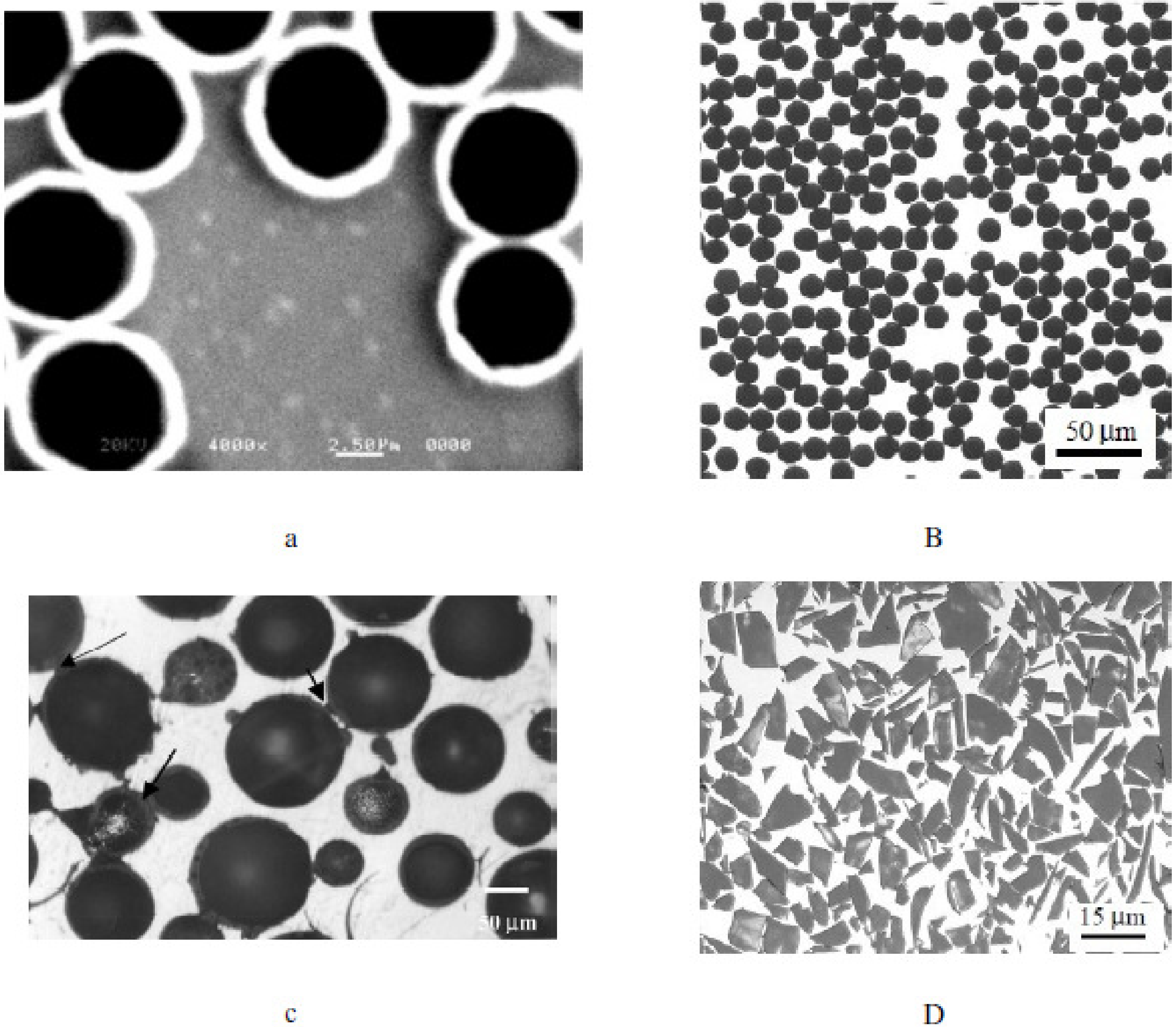


Fig. 6.1 (a) Transverse cross-section of continuous alumina fiber/magnesium alloy composite. (b) Typical microstructure of a silicon carbide particle/aluminum alloy composite. Note the angular nature of SiC particles and alignment of particles along the long axis



Micrographs of aluminum alloy matrix composites fabricated by pressure infiltration process. Preforms are made form a) nickel coated carbon fibers, b) Altex (γ-Al_2O_3) fibers, c) fly ash cenospheres and d) SiC particles.

Processing

- Liquid-State Processes
- Solid-State Processes
- Gaseous-Stare Processes

- **Liquid-State Processes:**
  - Near net shape
  - Faster processing time
  - Less expensive

- **Most common liquid-state processes:**
  - Casting, or liquid infiltration
  - Squeeze casting, or pressure infiltration
  - Spray co-diposition
  - In-situ processes

Liquid-State Processes

✓ Conventional casting

- Typically used with particulate reinforcements because of difficulties in casting fibrous preforms without pressure
- The particles and molten matrix are mixed and cast
- Secondary mechanical processing may be applied, e.g. extrusion or rolling

Liquid-State Processes

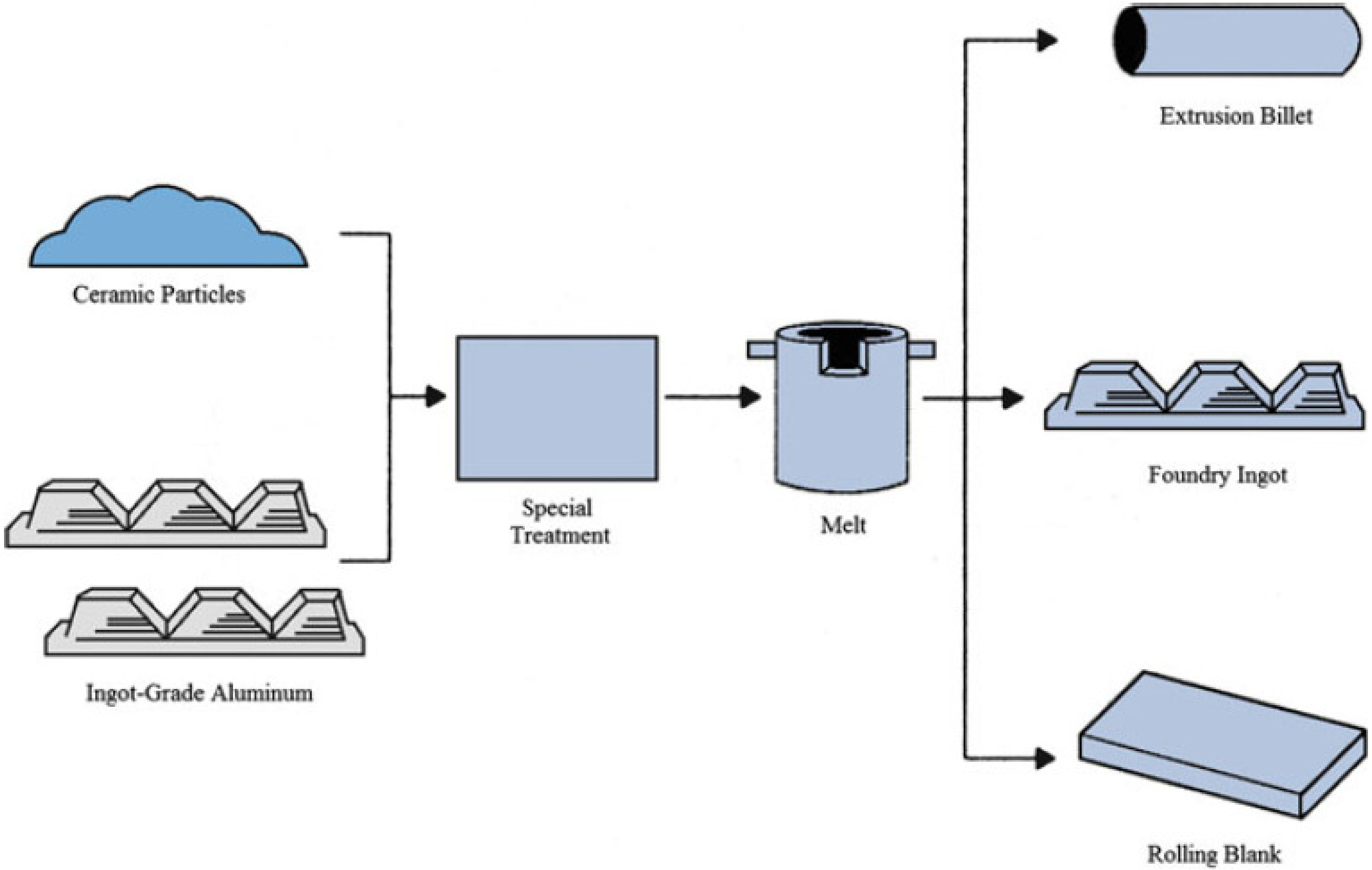


Fig. 6.2 Schematic of the Duralcan process

Liquid-State Processes

Modification to existing conventional processing:

1- Use alloys that minimize reactivity with the reinforcement, e.g. high silicon Al-Si alloys with SiC.

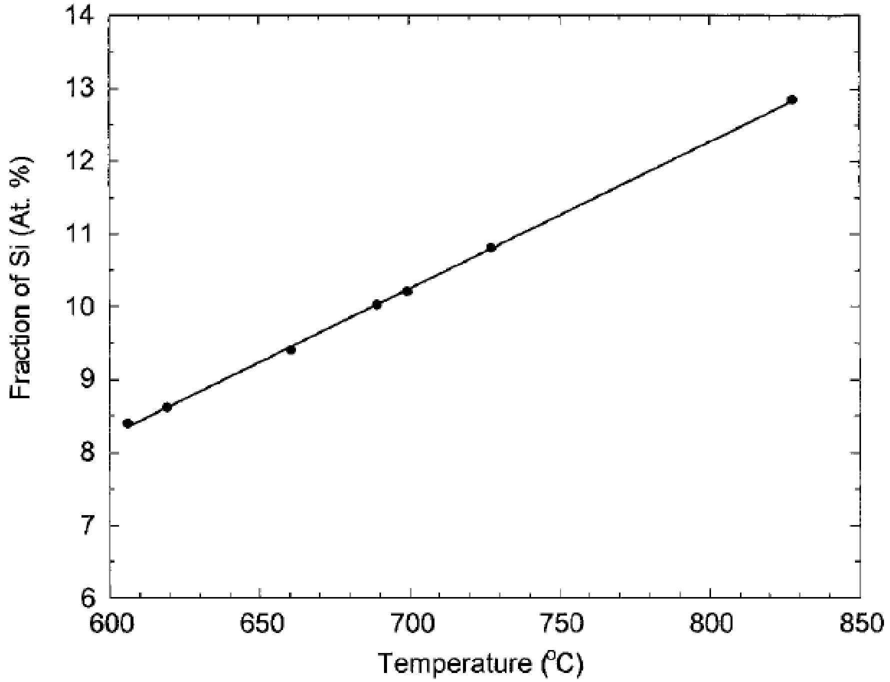


Fig. 4.2 Fraction of Si, at a given temperature, required to prevent formation of Al_4C_3 in an Al-Si/SiC composite (after Lloyd, 1997).

Liquid-State Processes

2- Higher processing temperature due to higher viscosity of the slurry, e.g. ~745 °C for Al-Si-SiC

- Viscosity of particulate composite, η_c,

$$\eta_c = \eta_m\left(1 + 2.5V_p + 10.05V_p^2\right)$$

η_m: the viscosity of the unreinforced metal
Vp: the volume fraction of particles

- For very small particles, e.g., 2–3 μm, the viscosity is even higher due to a very large interface region.

Liquid-State Processes

3- Protection by an inert gas to reduce oxidation of the melt

4- Stirring is often required to avoid sedimentation or flotation of the reinforcements.

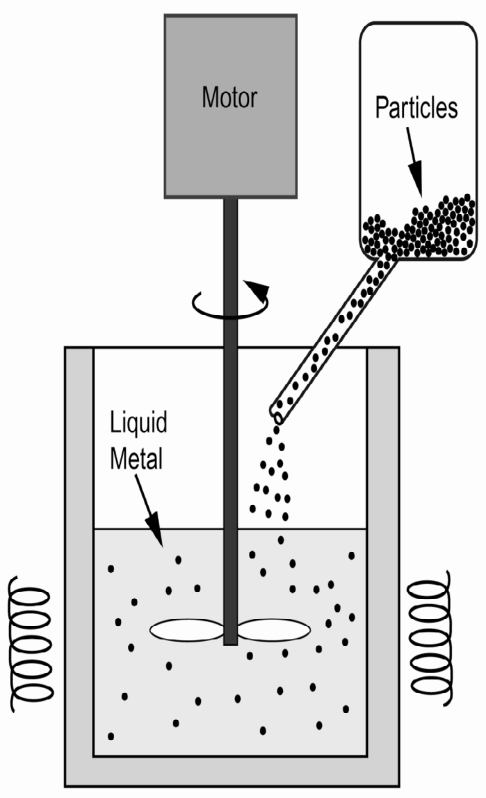
  - SiC density= 3.2 g/cm^3, Al density= 2.2 g/cm^3
  - Stirring: Mechanical, induction, ultrasonic vibration, …

- Stirring also improves wettability and permeability of the reinforcement in the molten matrix

…

Liquid-State Processes

✓Particle stirring (Vortex method)



Stirring of composite melt with ceramic particles to minimize settling of the particles during processing.

Liquid-State Processes

- Particles are stirred in the molten alloy
- Near net-shape (little further processing needed)
- Porosity should be minimized
- Particle surface treatments may be needed to improve wettability
- Prolonged contact between liquid metal and reinforcement → significant chemical reaction
- Typical lower limit on particle size: 15 μm!
- Max V_p ~ 15-20 %

Liquid-State Processes

Sedimentation of particles

- $\rho_{\text{particle}} > \rho_{\text{Matrix}}$ ⇒ settling down of particles according to the Stokes' law.

$$v_s = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g\, R^2$$

v_s = particle's settling velocity (m/s)

g = gravitational acceleration (m/s^2)

ρ_p = mass density of the particles (kg/m^3)

ρ_f = mass density of the fluid (kg/m^3)

μ = dynamic viscosity (kg /m.s)

✓ **Compocasting (semisolid composite casting)**

- Processing within the semisolid temperature range
  - Higher viscosity of the slurry
  - Existence of already solidified particles

  → Better distribution and retainment of the reinforcement

Liquid-State Processes

✓**Continuous fiber reinforced MMCs by vibration methods**

- Tows of fibers are passed through a liquid metal bath
- Individual fibers are wet by the molten metal
- Excess metal is wiped off, and a composite wire is produced

- A bundle of such wires can be consolidated by extrusion to make a composite.

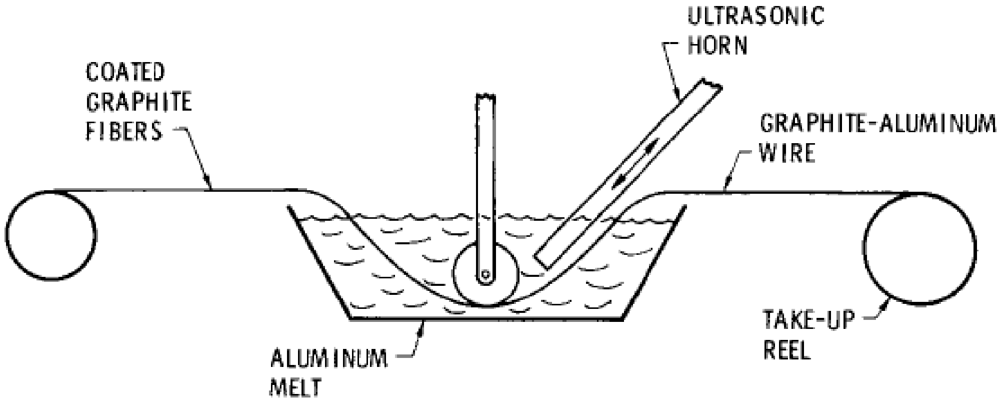


Figure 7.12 Ultrasonic vibration of an aluminum melt to assist the infiltration of a bundle of coated carbon fibers. From Ref. 14. (Reprinted by courtesy of Marcel Dekker, Inc.)

Liquid-State Processes

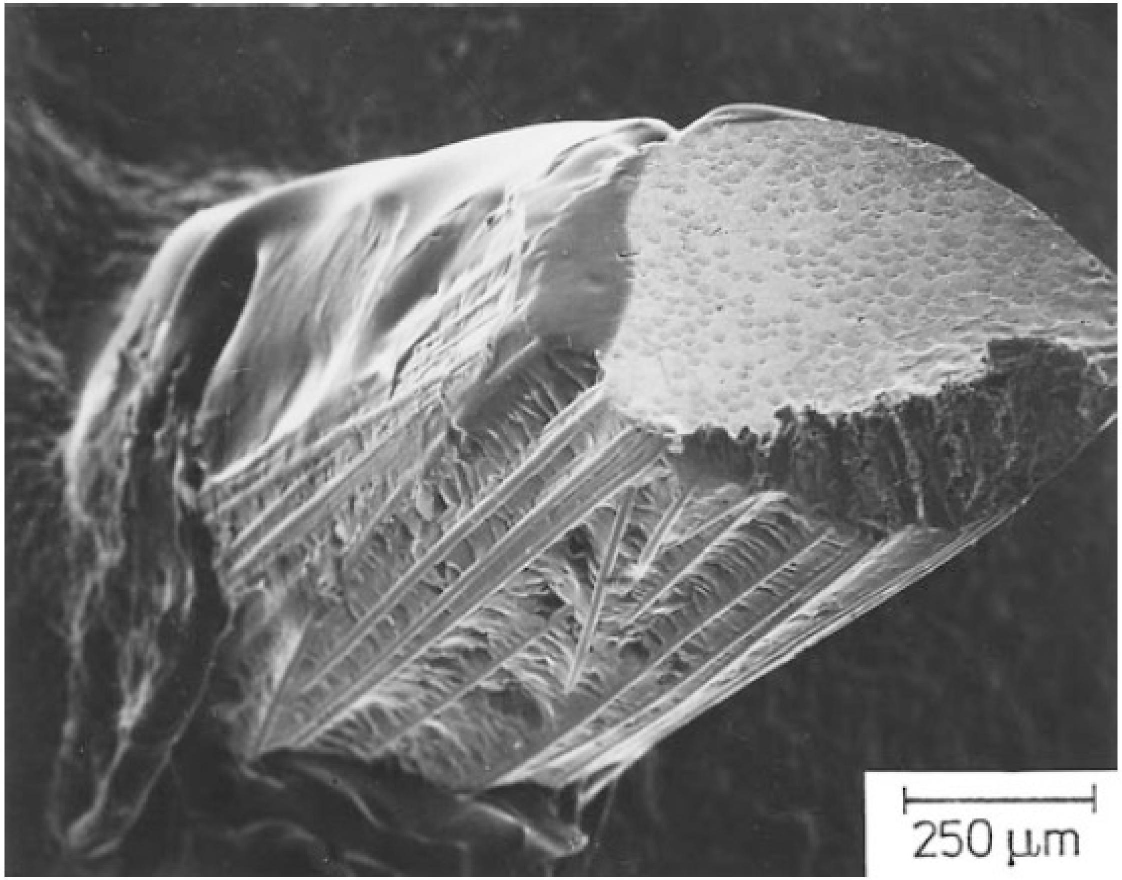
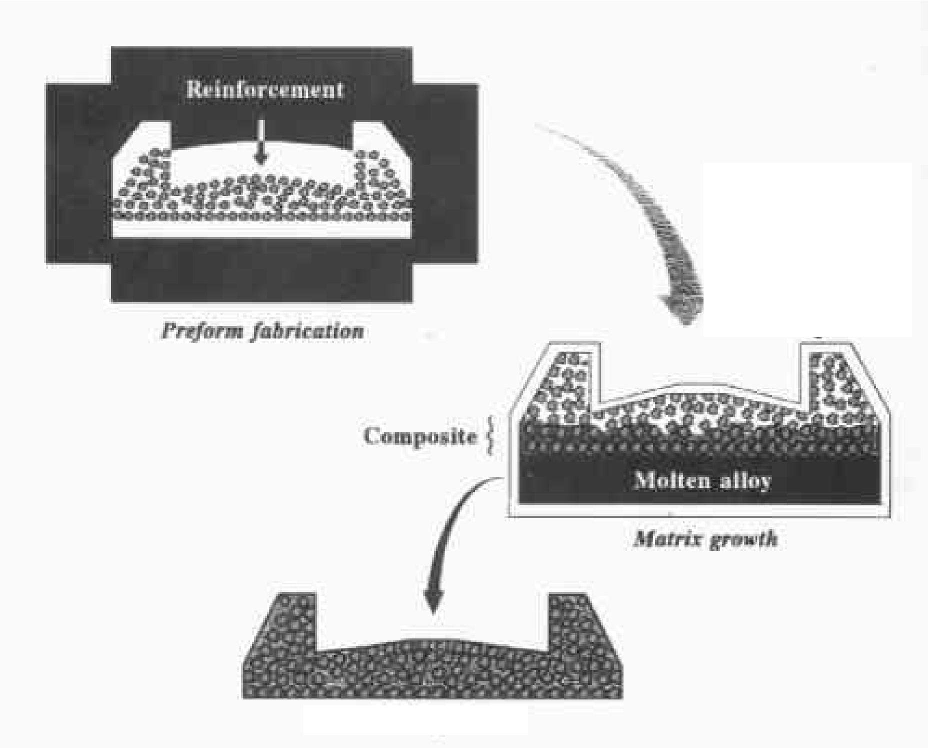


Fig. 6.3 A silicon carbide fiber/aluminum wire preform. SiC fibers can be seen in the transverse section as well as along the length the wire preform

Liquid-State Processes

✓ **Lanxide's Primex™ process**:

- A pressureless infiltration process
- Used with certain reactive metal alloys such Al–Mg to infiltrate ceramic preforms.
  - Processing temperature for an Al–Mg alloy: 750 -1000 °C in a nitrogen-rich atmosphere
  - Typical infiltration rates are less than 25 cm/h.



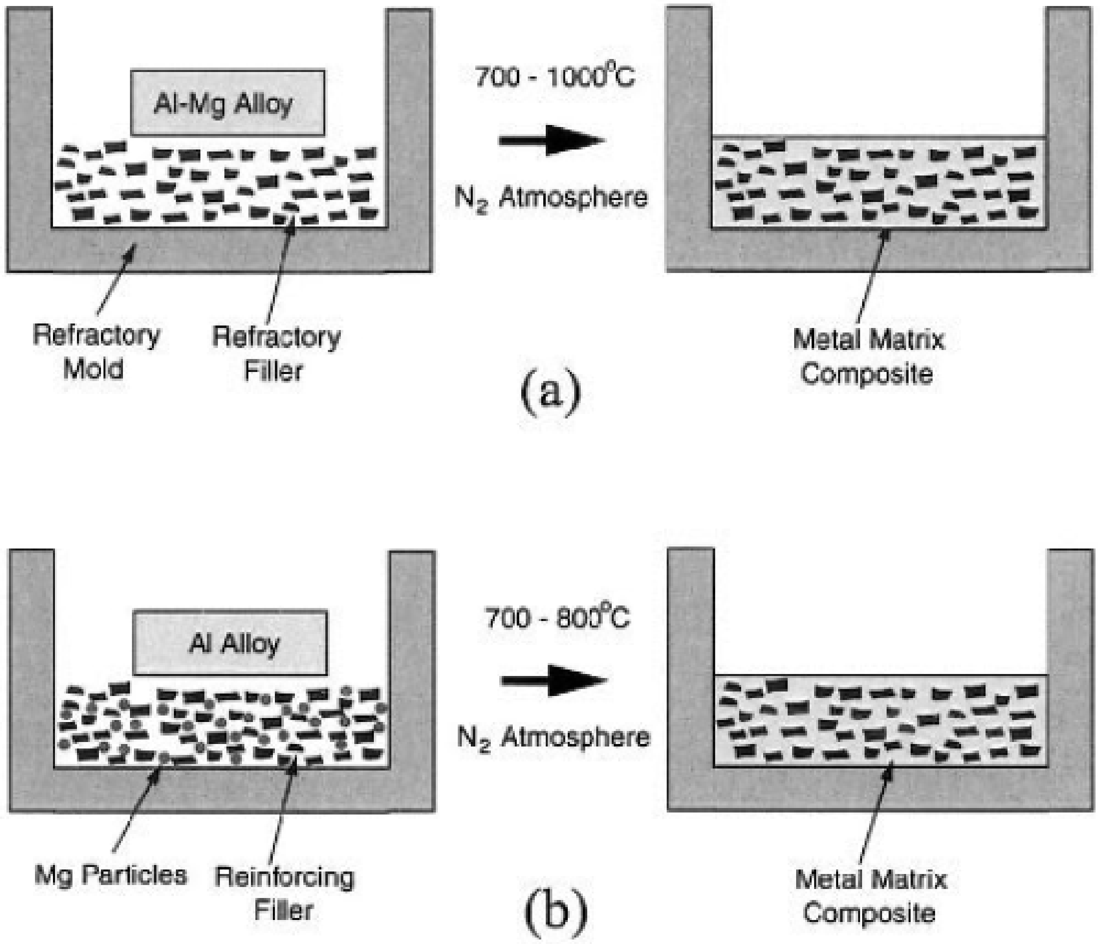
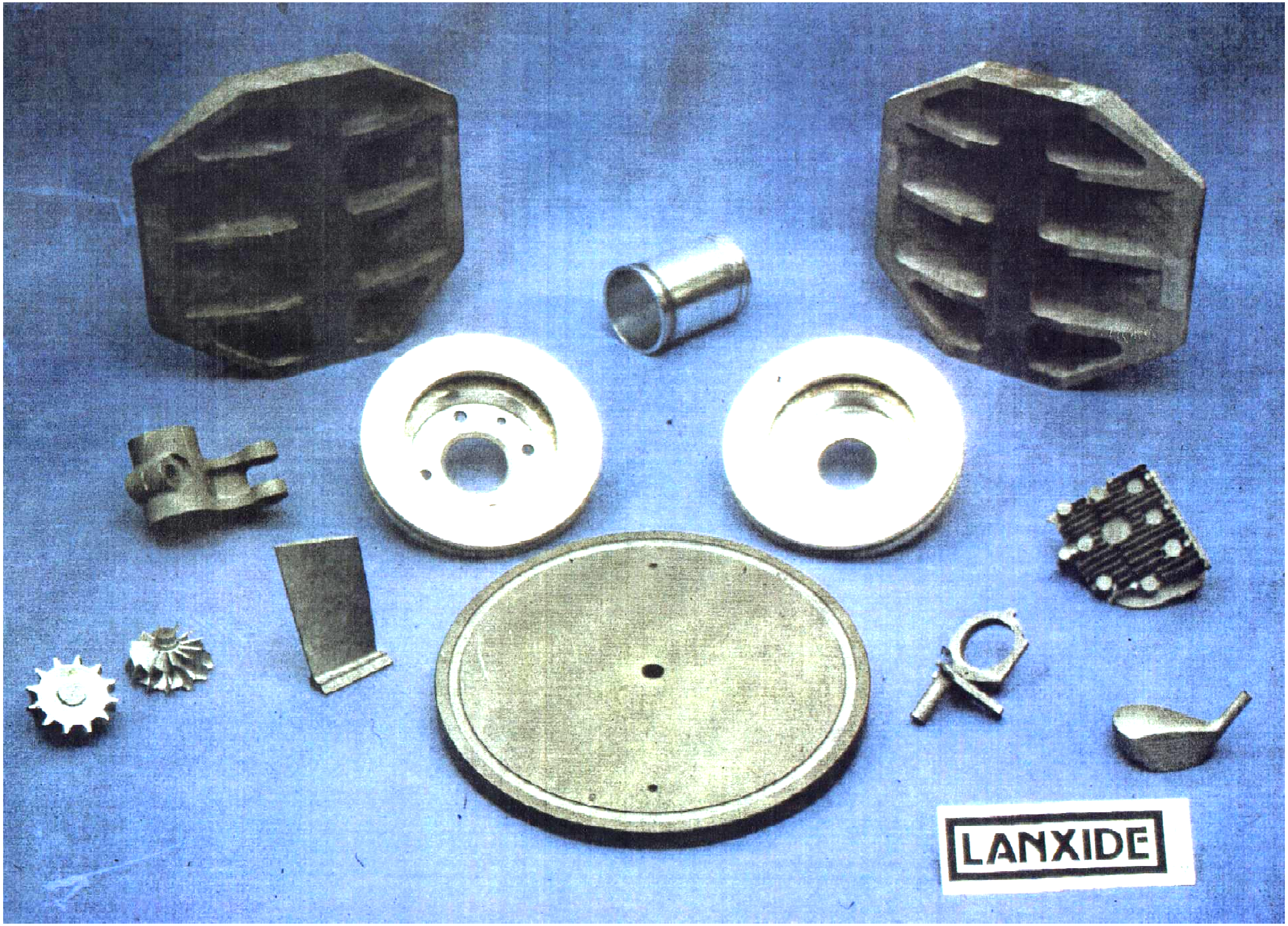


Fig. 4.8 Pressureless infiltration of MMCs: (a) Alloy matrix infiltration of particulate preform and (b) pure matrix infiltration of metallic alloy particle and ceramic particulate preform.

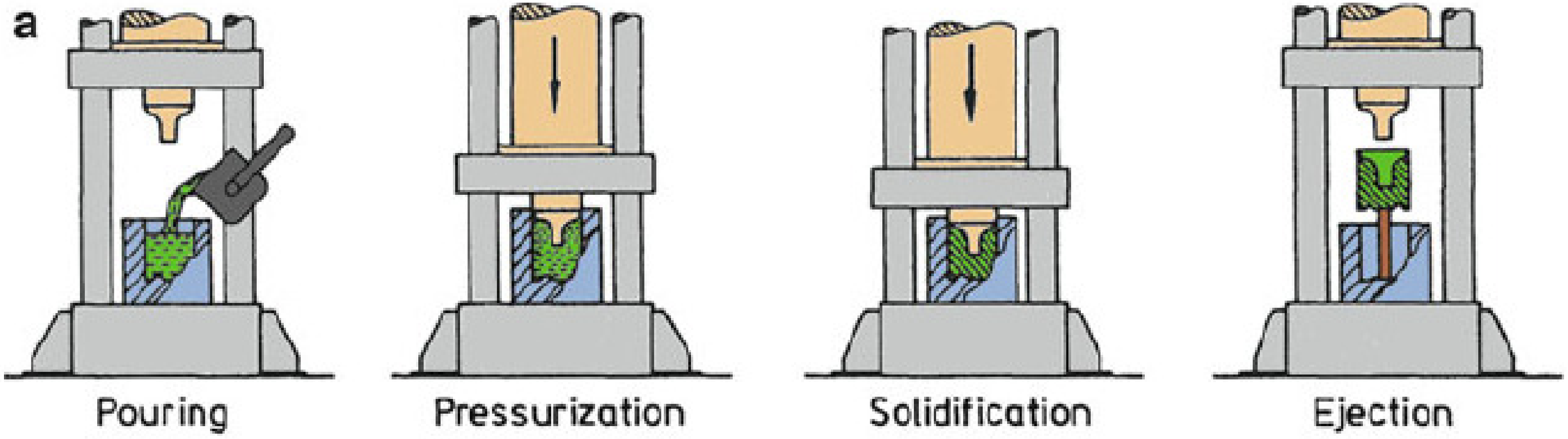


American Foundry Society · 105th Casting Congress, April 28 - May 1, 2001--Dallas, TX, USA

Liquid-State Processes

✓ **Squeeze casting / pressure infiltration:**

- **Squeeze casting**
  - Solidification of a composite slurry under a mechanically applied pressure



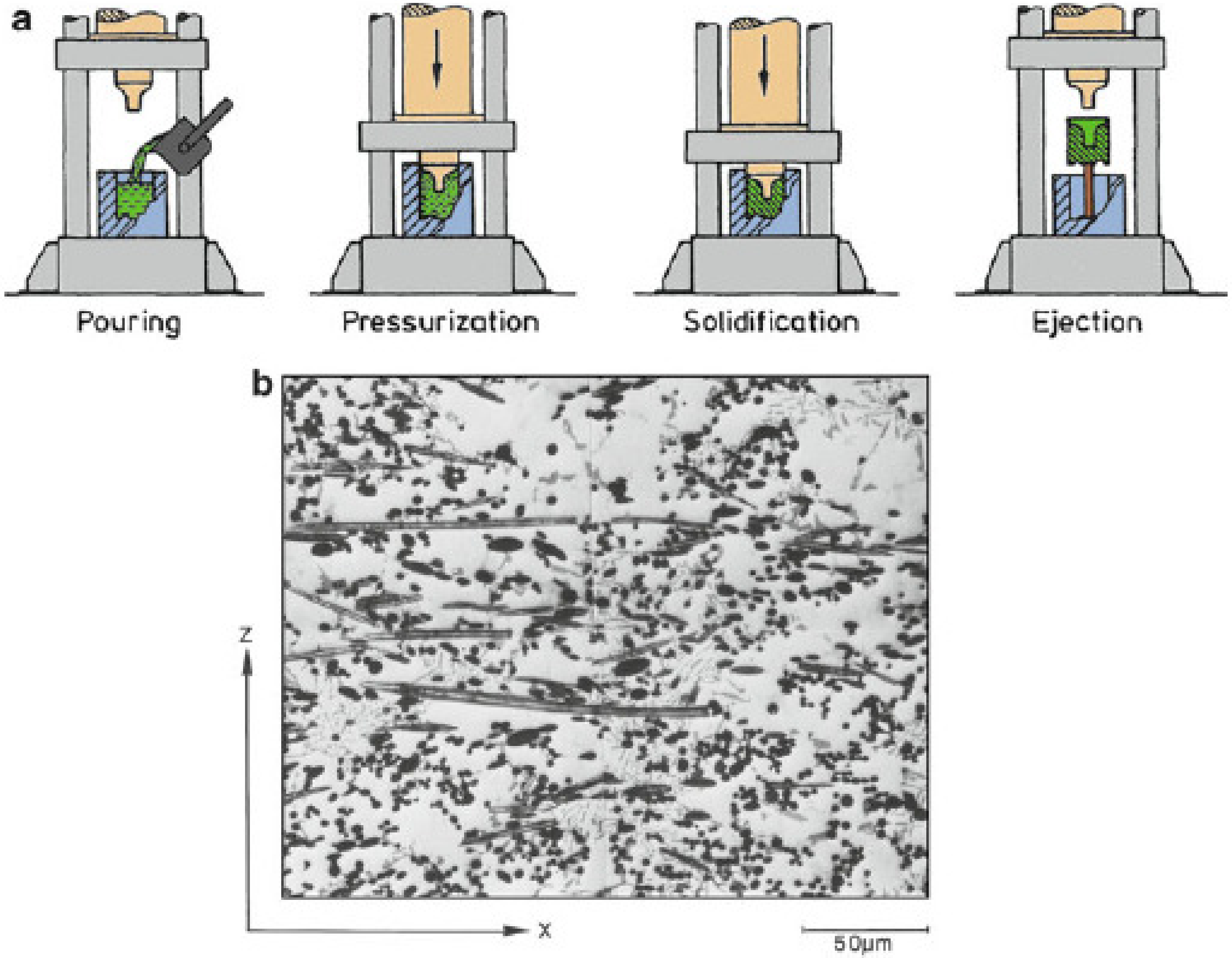
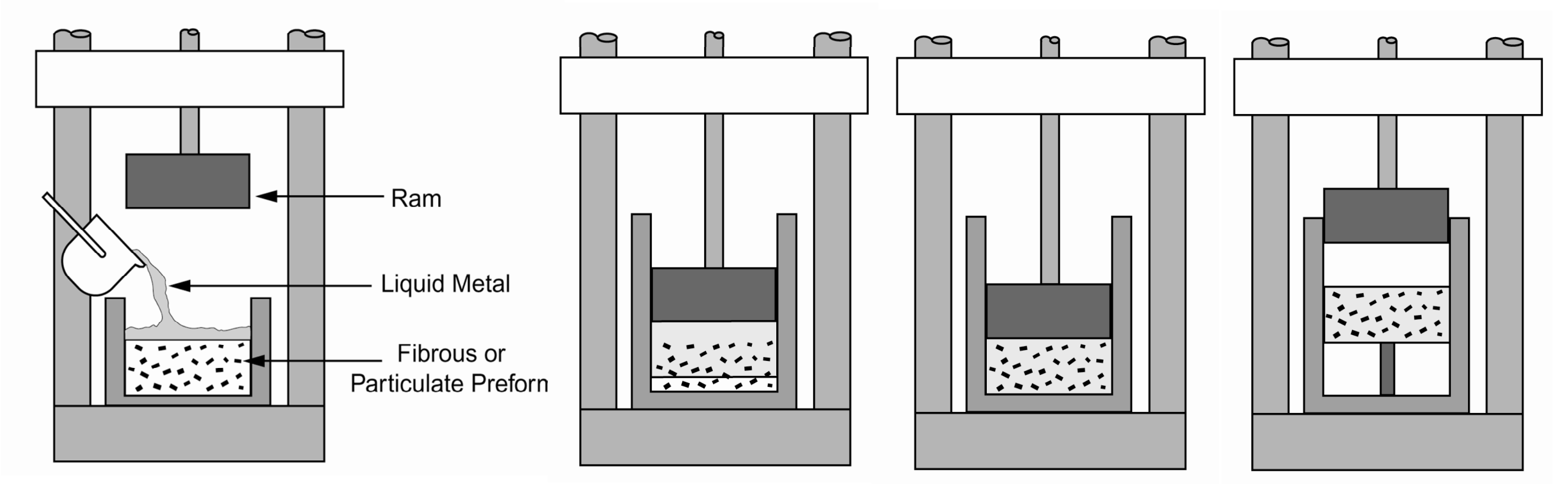


Fig. 6.5 (a) Squeeze casting technique of making a metal matrix composite. (b) The microstructure of Saffil alumina fiber/aluminum matrix composite made by squeeze casting. [Courtesy of G. Eggeler]

Liquid-State Processes

- **Pressure infiltration**
  - Forcing the liquid metal into a reinforcement preform.



Schematic of squeeze casting or liquid infiltration processing.

Liquid-State Processes

•Preform Manufacturing:

a- Press forming
b- Suction forming
c- Weaving
…

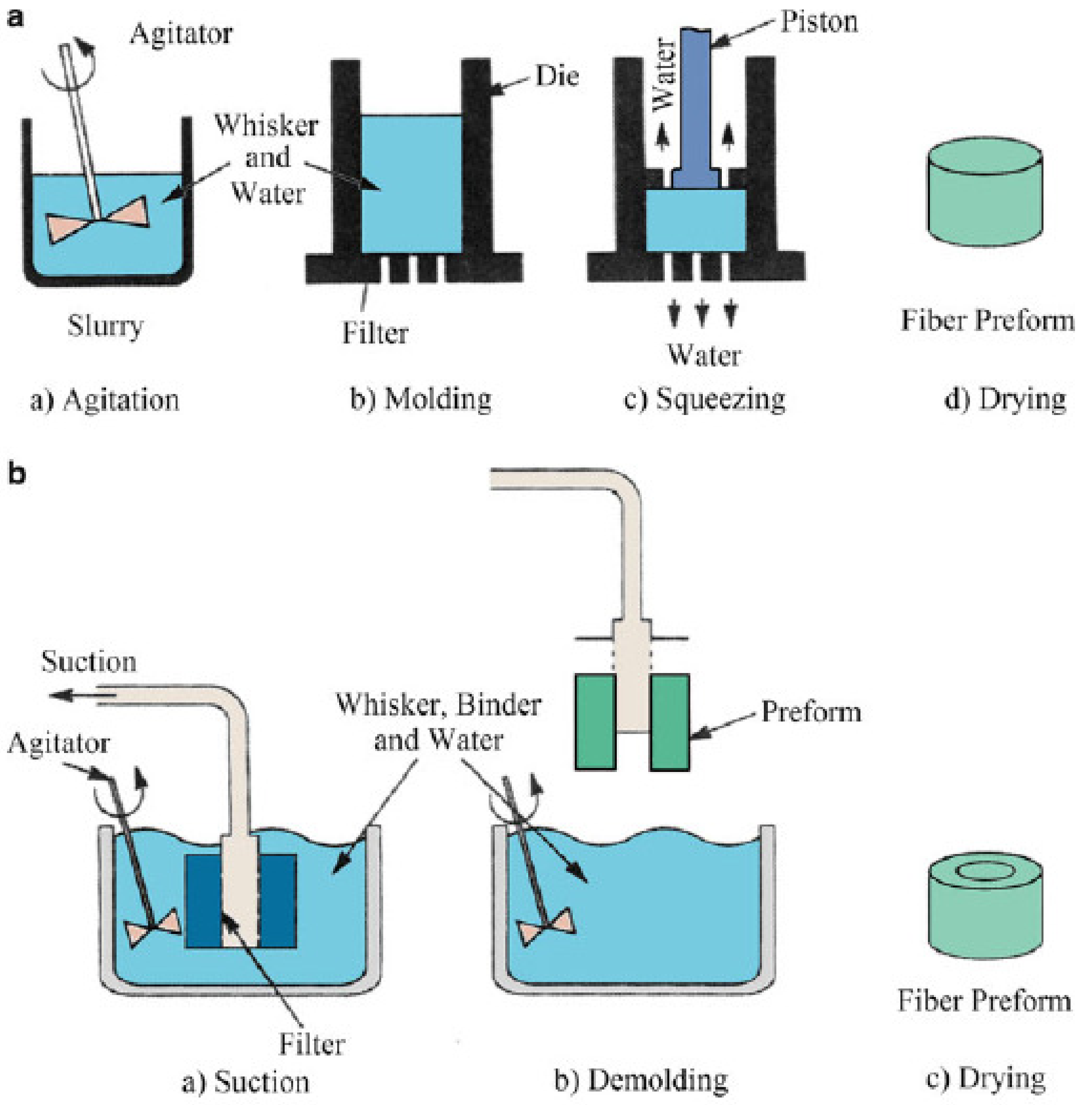
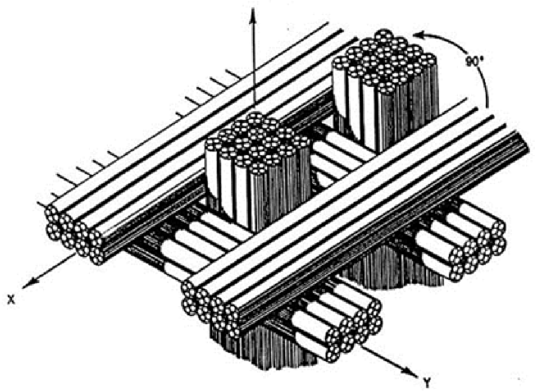


Fig. 6.4 (a) Press forming of a preform. (b) Suction forming of a preform

Liquid-State Processes

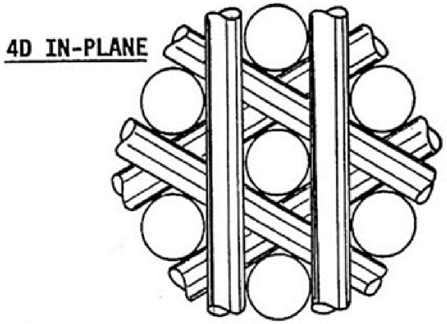
Structural Composite Architectural Forms

3D Blocks, Octagons

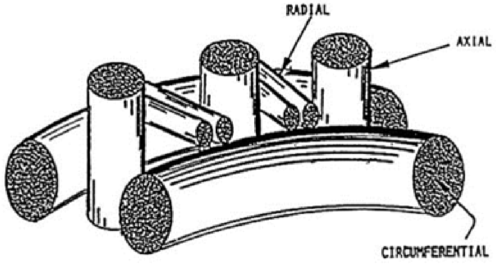


3D ORTHOGONAL WEAVE

4D Hexagons

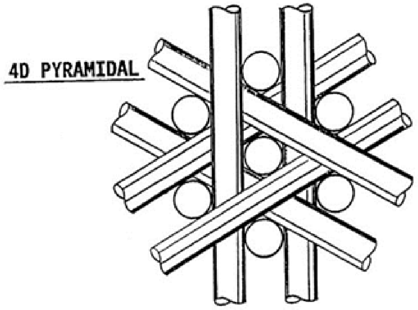


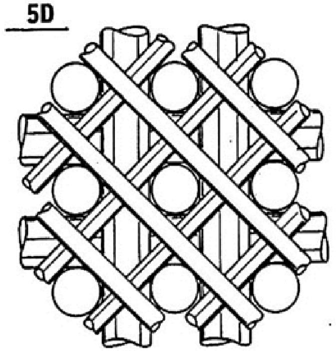
3D Cylinders & Frusta



3D CYLINDRICAL WEAVE

Alternative Multi-D Forms





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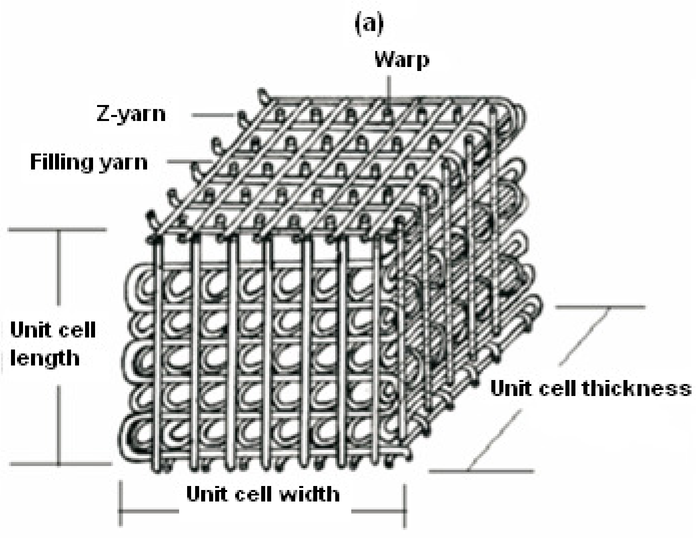
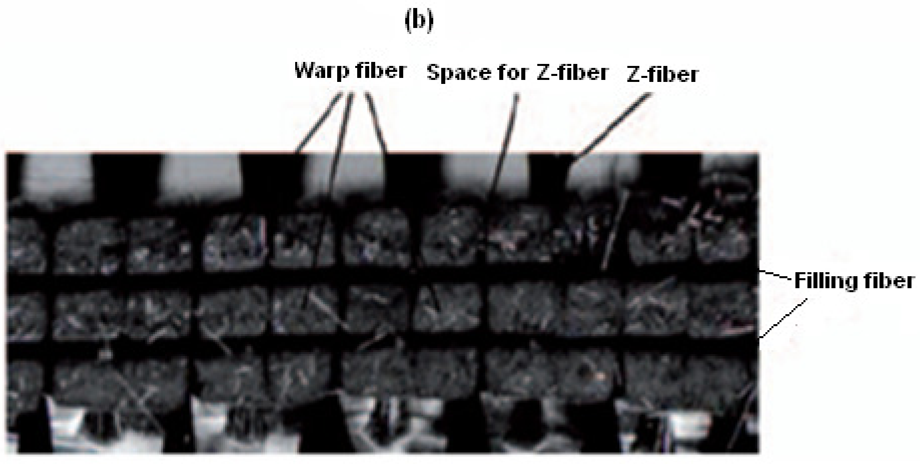
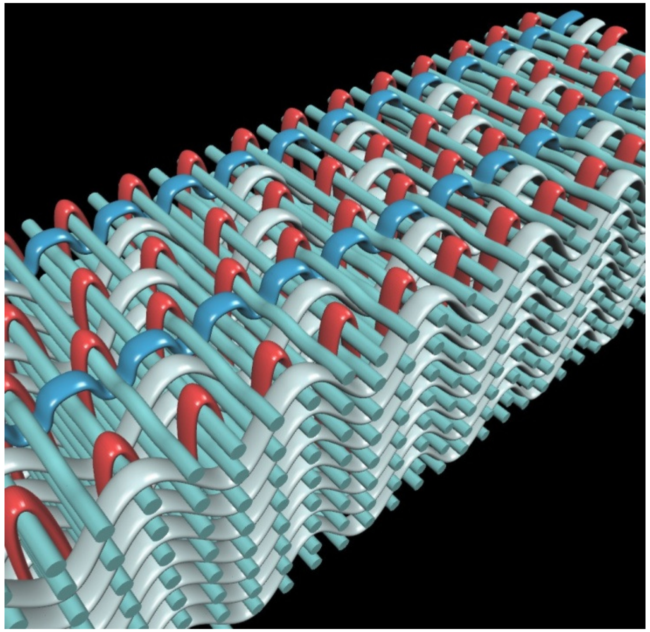
Liquid-State Processes







Liquid-State Processes

Permeability of porous medium by a fluid

- Darcy’s Law for single-phase fluid flow:

$$J = -\frac{k}{\eta}\nabla P$$

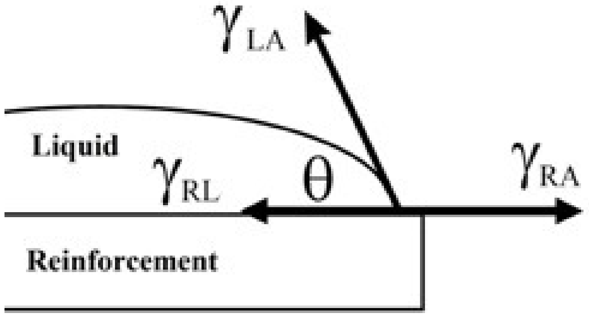
- J: Volume current density (i.e., volume/area×time) of the fluid)
- k: The permeability of a porous medium
- η: The fluid viscosity
- ∇P: The pressure gradient responsible for the fluid flow

•External pressure ↑
•Viscosity of the liquid ↓
•Permeability of the preform ↑

→ **Volume current density ↑**

Liquid-State Processes

- During infiltration, a given reinforcement/atmosphere surface is replaced with a reinforcement/liquid metal surface.



- If $\sigma_{RA} > \sigma_{RL} \rightarrow$ **Spontaneous infiltration** of molten metal into the preform!

- If $\sigma_{RA} < \sigma_{RL}$, the process cannot be spontaneous
  → Some work is required to make the melt flow in the interstices of the preform.

- This work should be supplied by an external source such as *vacuum* in the preform or *gas/piston pressure* on the melt.

Liquid-State Processes

- The minimum pressure required to infiltrate the melt into the preform can be written as

$$P \propto S_f\,(\sigma_{RL} - \sigma_{RA})$$

  - $S_{f:}$ The specific surface area of the preform (interface per unit volume of the matrix)
  - Young's Eq.: $\sigma_{RA} - \sigma_{RL} = \sigma_{LA}\,.\,\mathrm{Cos}\,\theta$

$$\Longrightarrow \quad P \propto -S_f\,.\,\sigma_{LA}\,.\,\mathrm{Cos}\,\theta$$

- If melt is to be forced through a channel of width r:

$$\Longrightarrow \quad P \propto -(S_f\,.\,\sigma_{LA}\,.\,\mathrm{Cos}\,\theta)/\,r$$

Liquid-State Processes

- Infiltration is improved by increasing σ_{RA} and decreasing σ_{RL}.
- Reducing σ_{LA} at constant $\sigma_{RA} - \sigma_{RL}$ will decrease the wetting angle in wetting systems, but cannot transform a non-wetting system ($\theta > 90°$) to a wetting system ($\theta < 90°$).
- S_f and r are dependent on volume fraction and size of the reinforcements.
- For most metal-ceramic systems (non-wetting systems), decreasing the size of reinforcement particles/fibers or increasing the volume fraction of the reinforcement deters infiltration.
- A preform with a higher specific area and smaller interstitial channels requires a higher pressure for infiltration.

Liquid-State Processes

- Main variables:
  - Reinforcements temperature
  - Melt temperature
  - Die temperature
  - Applied pressure
  - Rate of pressure application (Rate of infiltration)
  - Alloy composition
  - Reinforcement composition

Liquid-State Processes

Squeeze cast/Pressure infiltrated composites

- A threshold (Min.) pressure is required for infiltration.

- Applied pressure should not exceed a Max. value!
  - Applied pressures: ~70–100 MPa
    - Makes the molten metal to penetrate the fiber preform and bond the fibers
    - Higher pressures may result in preform movement or failure!

- Short dwell time at high temperature
  - Minimal reaction between the reinforcement and molten metal

Liquid-State Processes

- Can be free from common casting defects such as porosity and shrinkage cavities
- Macrosegragation may occur!
- Selective reinforcement is possible
- Casting of wrought alloys is possible
- Near net-shape

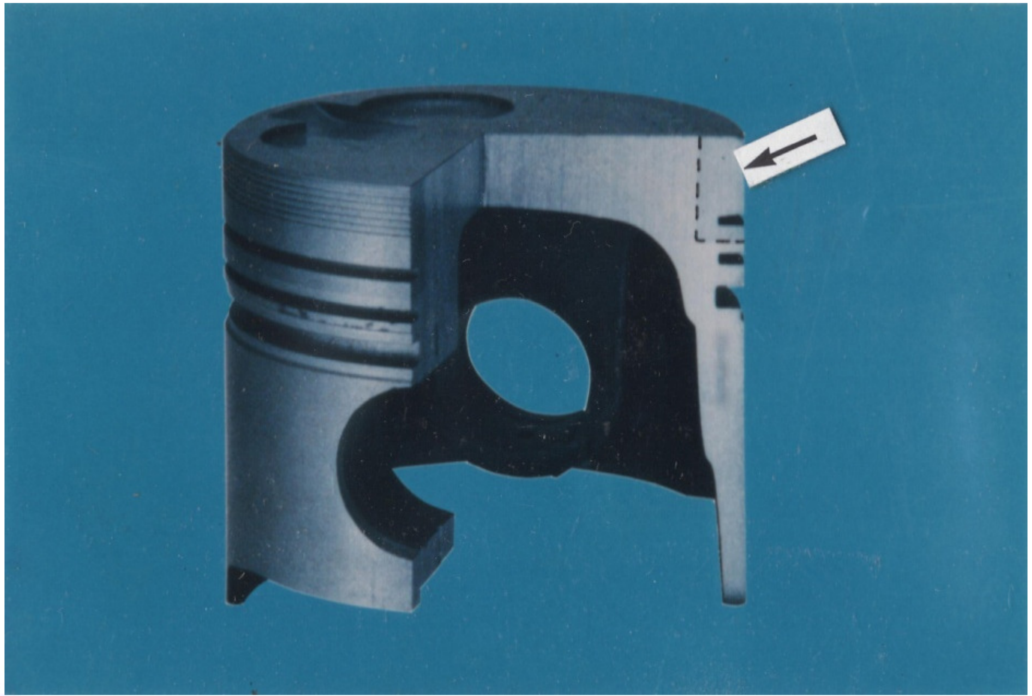
Liquid-State Processes

- Selective reinforcement
  - Combustion bowl and ring grooves in diesel engine pistons
  - Selective reinforcing with ceramic fibers instead of the Ni-resist cast iron inserts
  - Much superior products and 10% weight reduction

Diesel engine piston

(Al/Alumina fiber composite)

made by squeeze casting



Liquid-State Processes

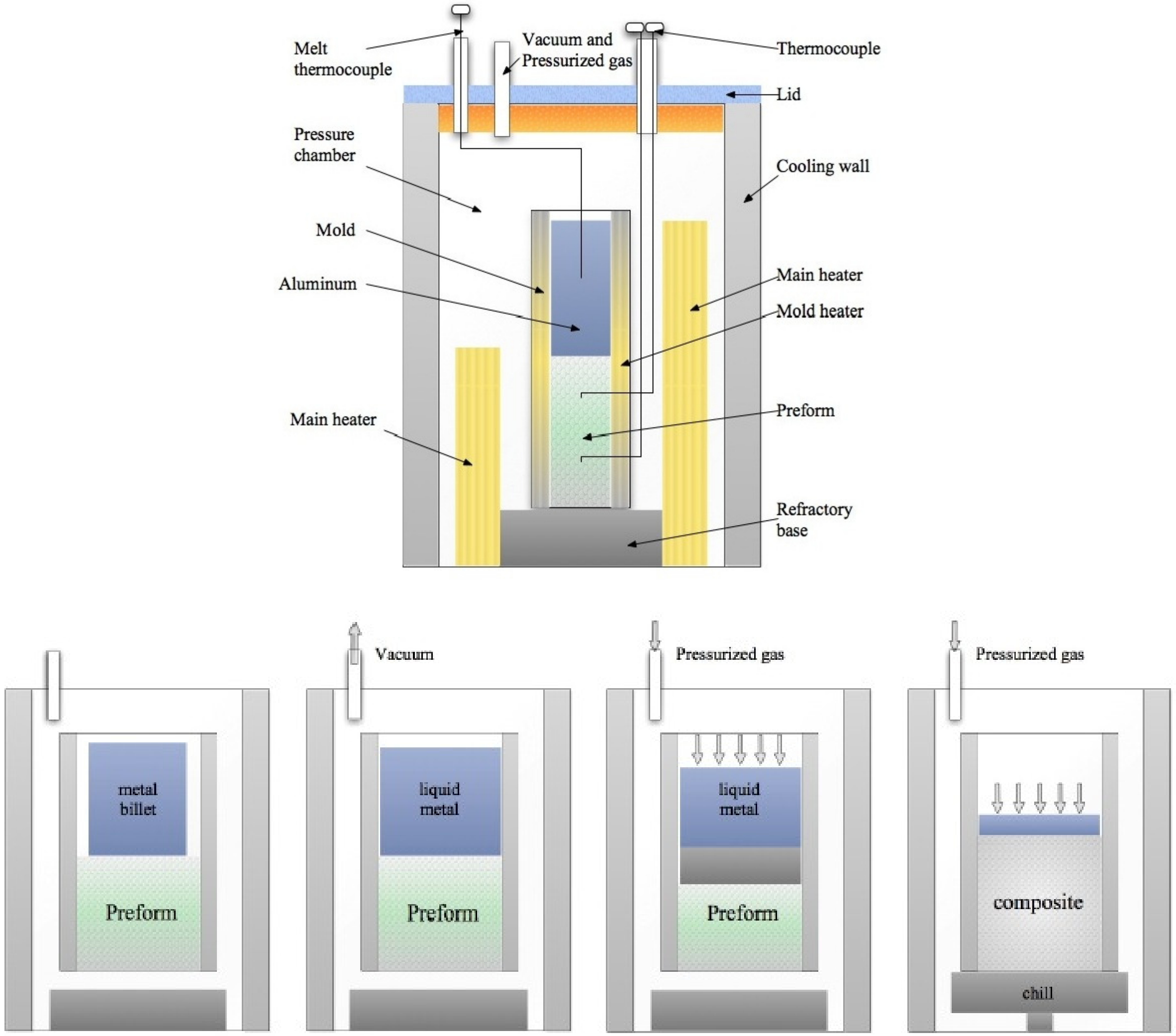
Pressure Gas Infiltration of a preform

- Controlled environment of a pressure vessel
- Rather high reinforcement volume fractions
- Reinforcement: particles, long or short fibers, whiskers, …
- Complex-shaped structures

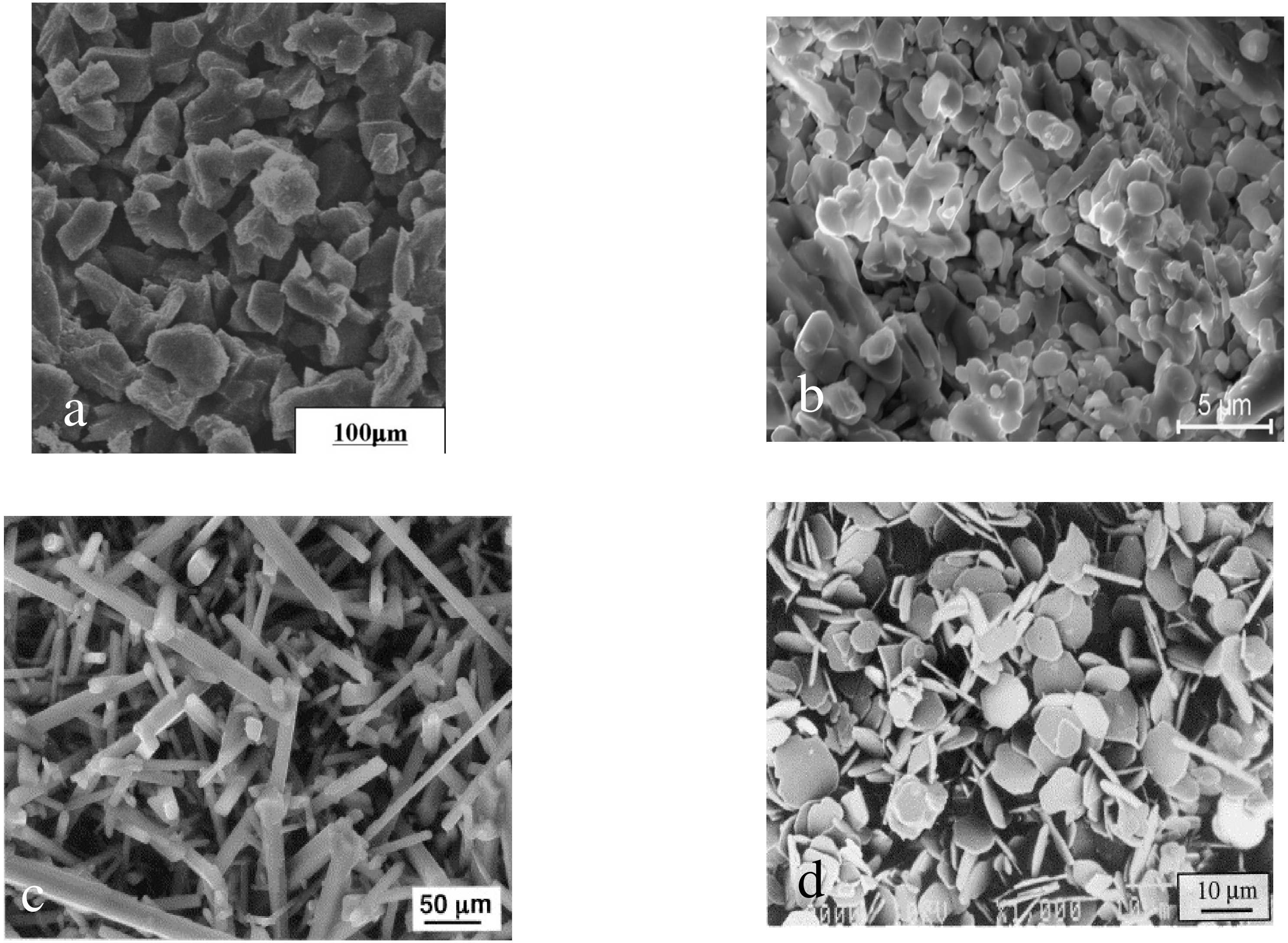
Process involves:

- Melting the matrix alloy in a crucible in vacuum
- Separately heating the preform
- Molten matrix material is poured onto the fibers
- Argon gas pressure forces the melt to infiltrate the preform
- The melt generally contains additives to aid in wetting the fibers.

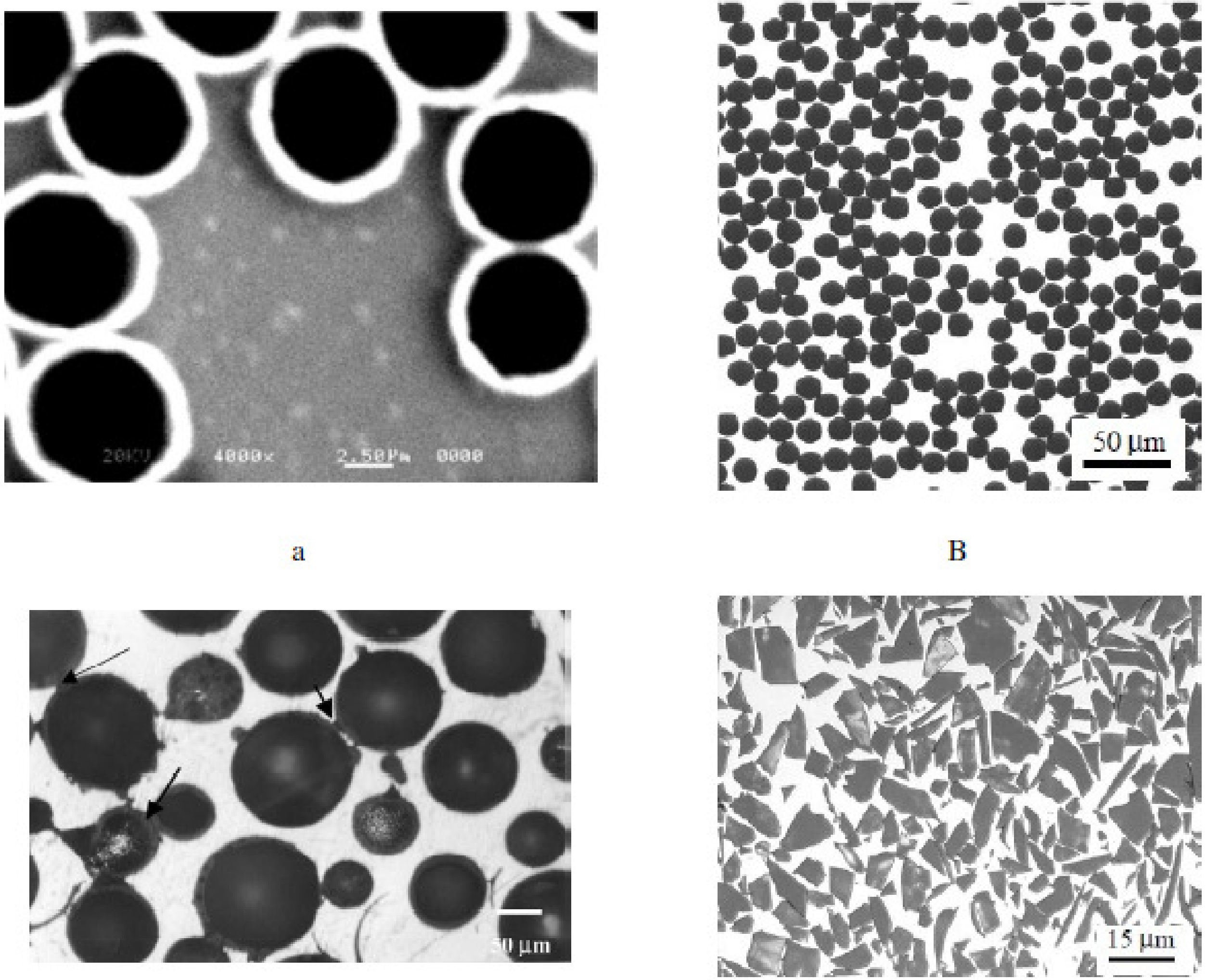
Liquid-State Processes



Liquid metal gas infiltration process



a) SiC particles, b) Al_2O_3 particles, c) aluminum borate whiskers and d) Alumina flakes preforms used in pressure infiltration process



a B

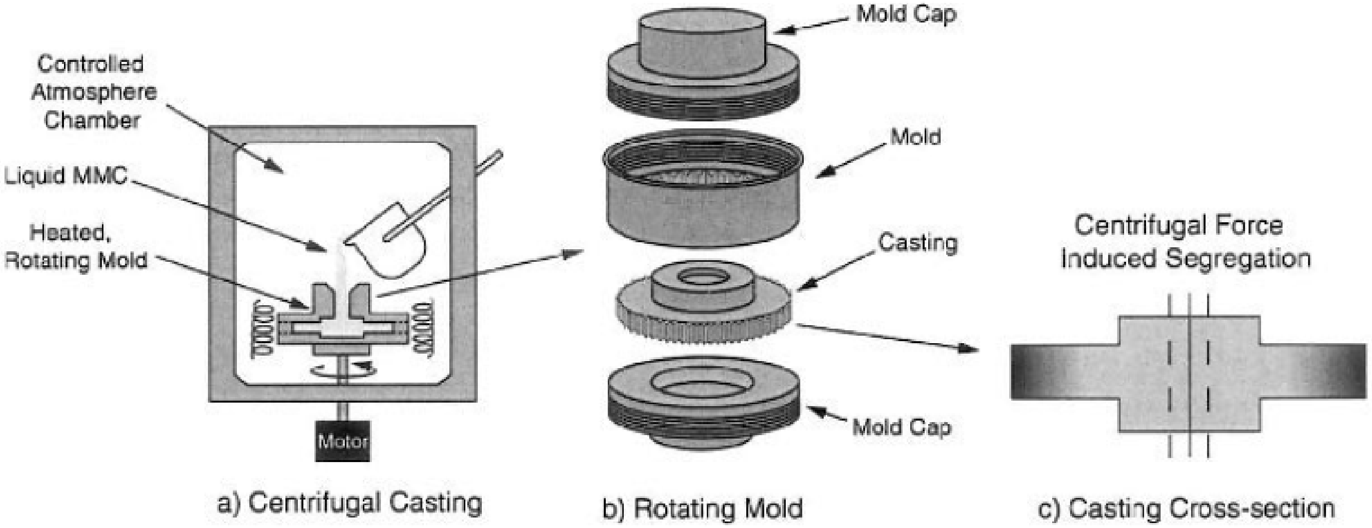
c D

Micrographs of aluminum alloy matrix composites fabricated by pressure infiltration process. Preforms are made form a) nickel coated carbon fibers, b) Altex (γ-Al_2O_3) fibers, c) fly ash cenospheres and d) SiC particles.

Liquid-State Processes

Centrifugal Casting

- Inducing a centrifugal force during casting
- Obtaining a gradient in reinforcement volume fraction
- Optimal placement of the reinforcement



a) Centrifugal Casting b) Rotating Mold c) Casting Cross-section

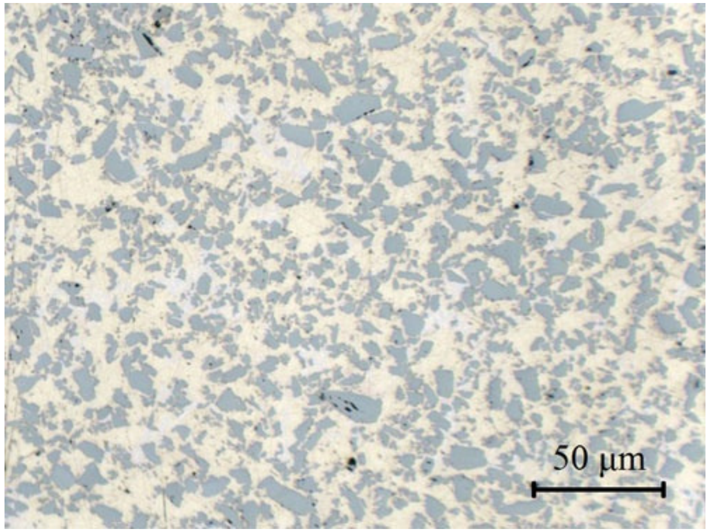
Fig. 4.4 (a) Schematic of centrifugal casting process, (b) rotating mold, and (c) cross-section of finished casting with intentionally-segregated reinforcement.

Liquid-State Processes

Brake rotors

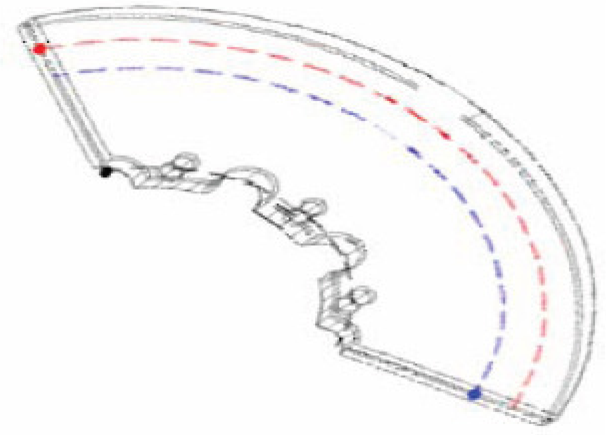
- Wear resistance on the rotor face
- Easier machining on the hub area

Microstructure of a centrifugally cast WC/bronze composite



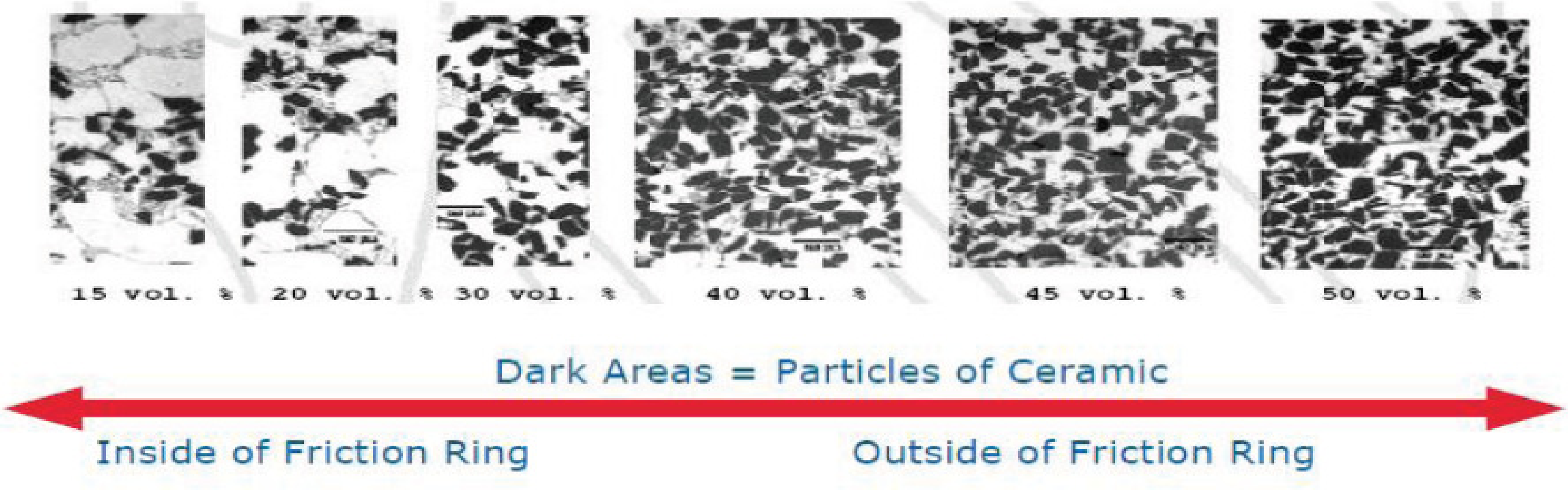
Liquid-State Processes

- **Motor cycle brake rotor**



Blue: Lower vol % SiC

Red: Higher vol % SiC



Liquid-State Processes

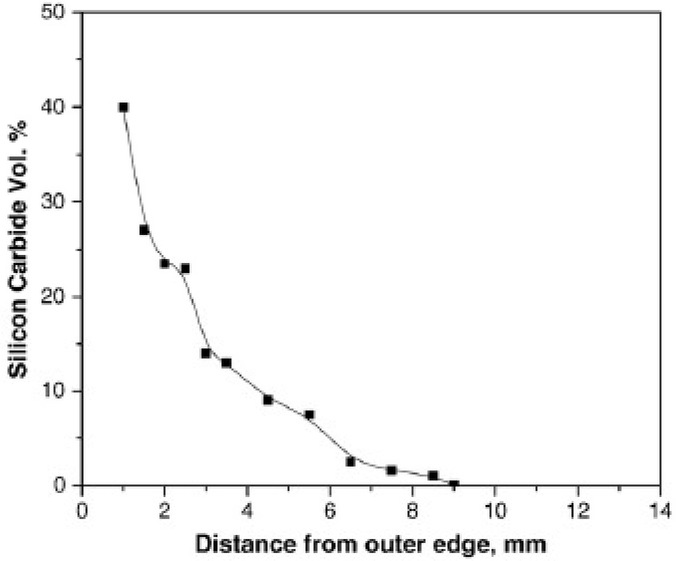


Fig. 7 – Graded distribution SiC particle from the outer periphery of the Al(2124)-SiC centrifugal cast ring.

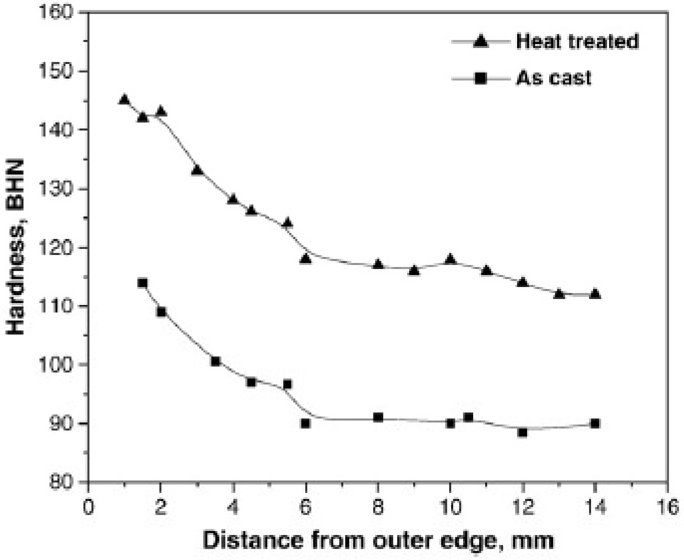
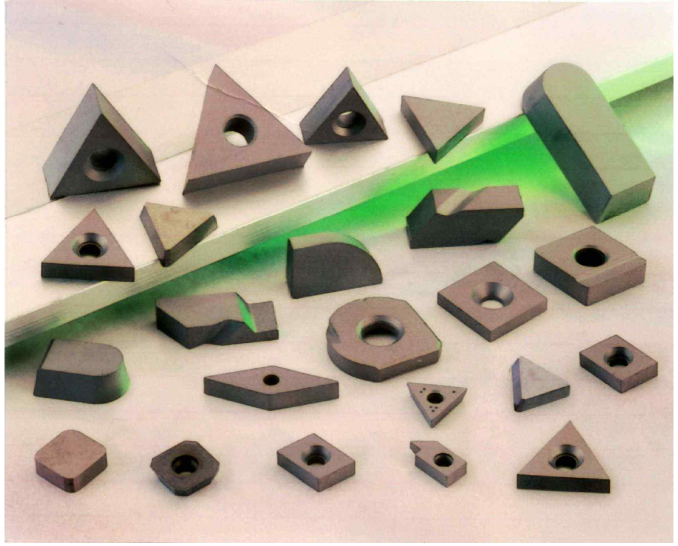


Fig. 8 – Variation in hardness from outer edge of as-cast and heat treated Al(2124)-SiC functionally graded composites.

T.P.D. Rajan, R.M. Pillai, B.C. Pai , MATERIAL SCHARACTERIZATION 61 (2010) 923–928

Liquid-State Processes

Processing of WC/Co Composites



- Cemented carbides = WC/Co MMC
- Liquid cobalt wets WC particles very easily ($\theta=0$)

➢ Milling of WC particles with Co powder → spherical granules of WC/Co

➢ Compaction under pressure (50–150 MPa) to make green compacts having 65% of the theoretical density

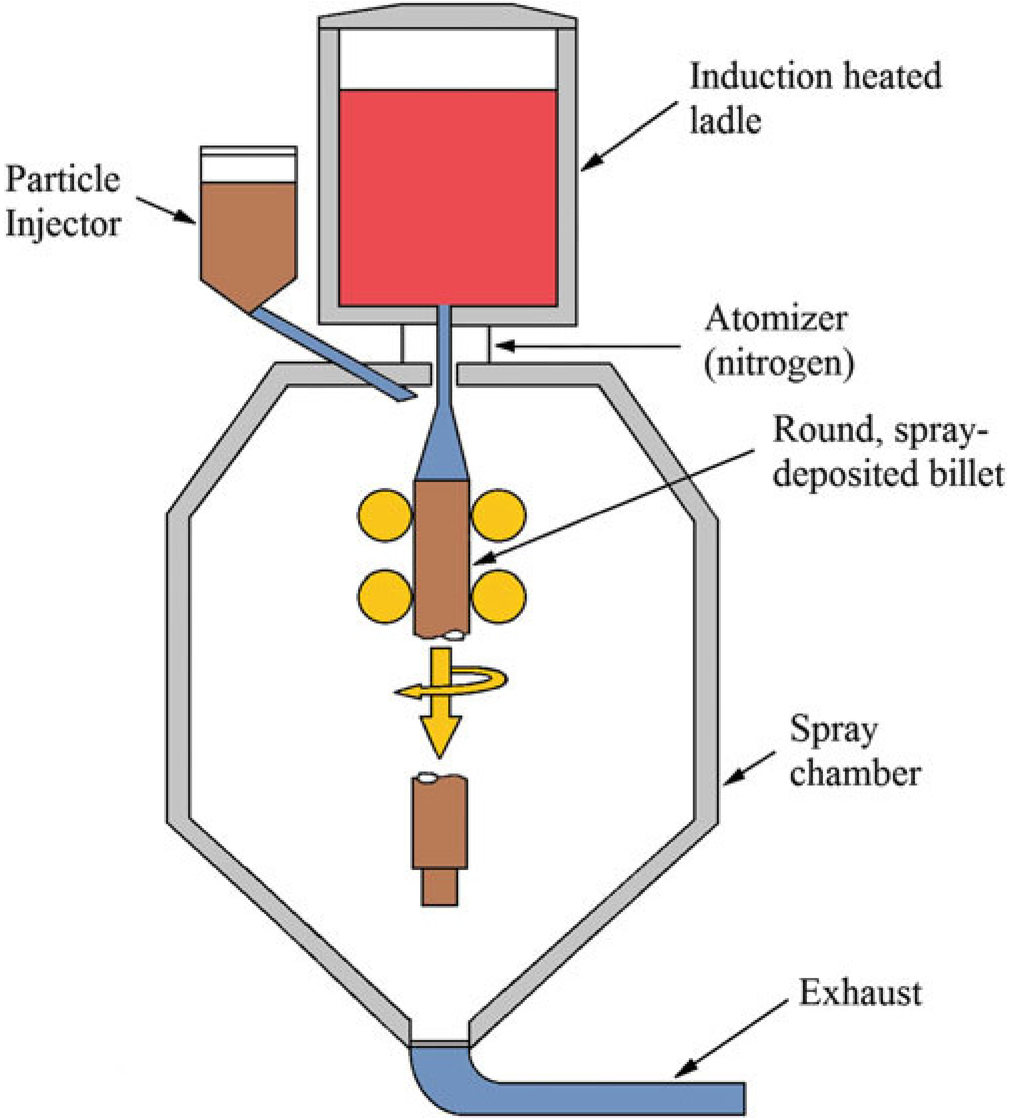
➢ Pressureless liquid phase sintering

  – Good infiltration of WC particles by liquid cobalt occurs because of capillary action .

Liquid-State Processes

Spray-Forming

- A molten alloy matrix is atomized using a spray gun
- Preheated dry ceramic particles are injected into this stream
- Produces a porous preform
- The co-sprayed MMC is subjected to scalping, consolidation, and secondary finishing processes.



Schematic of the spray forming process

Liquid-State Processes

Fig. 11.12 Spray formed billets of PEAK Werkstoff GmbH.

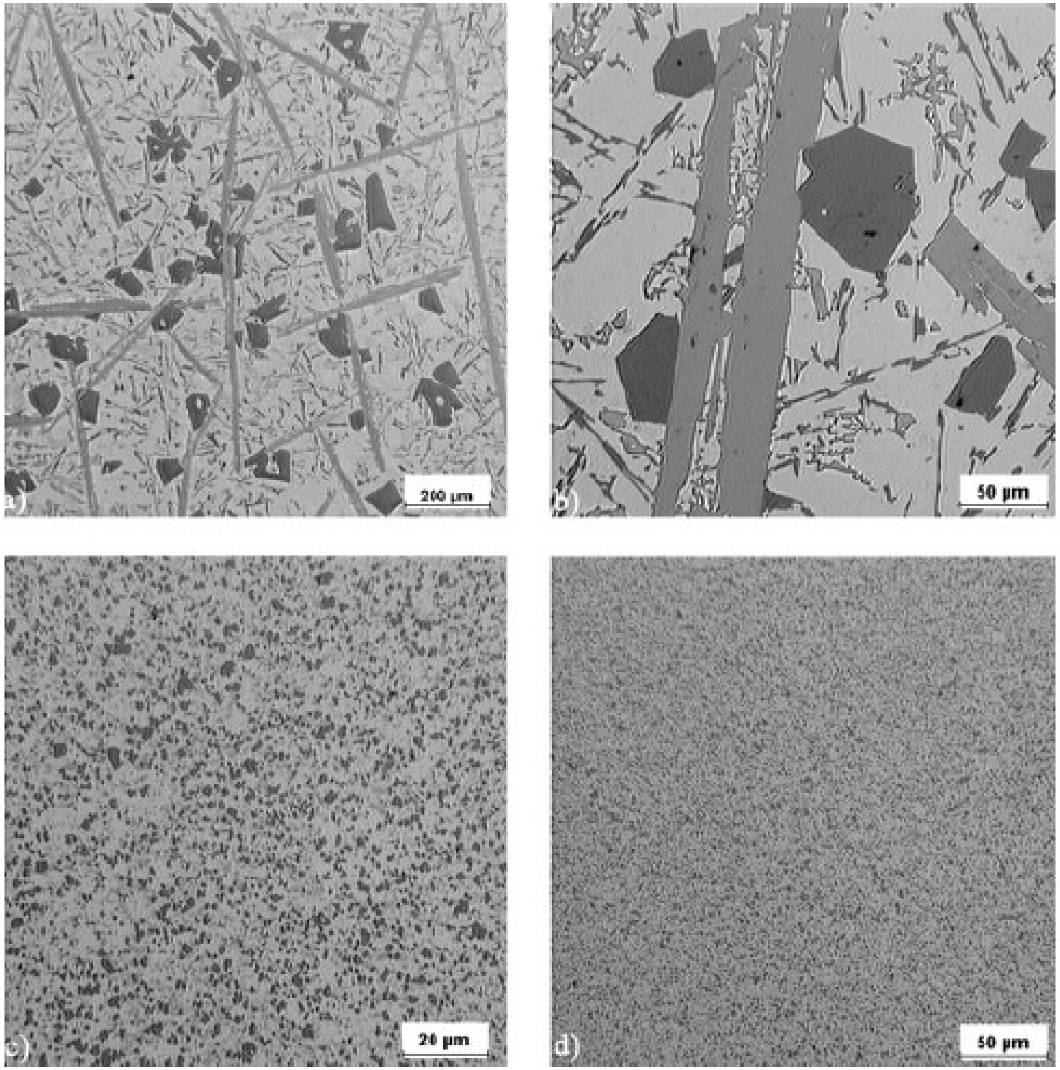
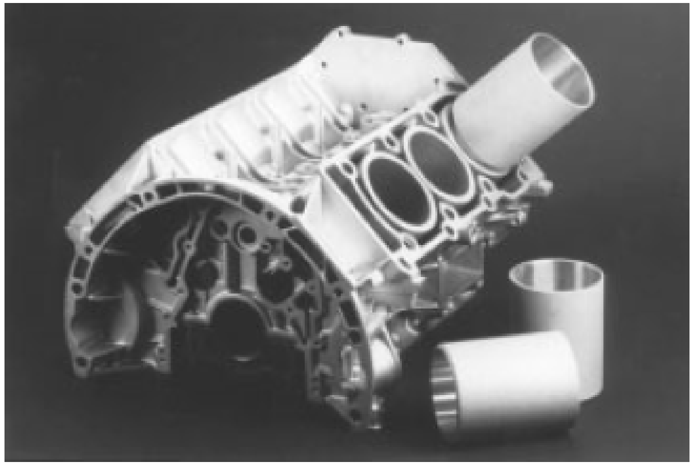


Fig. 11.7 Microstructure of alloy AlSi20Fe5Ni2, “as cast” and “as sprayed”. (a) as cast 50×; (b) as cast 200×; (c) spray formed 200×; (d) spray formed 500×.

Liquid-State Processes

- Extremely short flight times →formation of deleterious reaction products avoided

- High production rate: 6-10 kg/min



High pressure die cast crankcase with indirect extruded cylinder liners of the spray formed alloy AlSi25Cu4Mg.

- Great flexibility in making different types of composites, e.g.
  - Making in situ laminates using two sprayers
  - Selective reinforcement
  - Functionally graded Materials (FMGs) are possible