CHAPTER 6

Metal Matrix Composites

Metal Matrix Composites

- High specific strength, high specific modulus, good toughness, 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 composites
  - In-situ composites
  - Nano composites
  - Unconventional 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

Cost of Commercial MMC Materials and Reinforcements

Stir-casting MMC (PRM):	**5 – 25 €/kg (e.g., Duralcan)**
Sprayed MMC (PRM):	**10 – 50 €/kg (e.g., Peak)**
PM (PRM):	**15 – 150 €/kg (e.g., AMC, DWA); Dartal: 28 €/kg**
Particles:	**1 – 10 €/kg (except B_4C: 40 €/kg)**
Short ceramic fibre preform:	**200 €/kg (Saffil)**
Carbon multifilaments:	**15 (HT) – 2000 (HM) €/kg**
Ceramic multifilaments:	**> 350 €/kg**
Ceramic monofilaments:	**> 5000 €/kg**

Consequence:

Fibres are competitive only for small components or as selective reinforcement!

acc: Achim Schoberth (EADS), "MMC for Aerospace Applications", DFG, AK CMC, Bremen, 11. März 2005

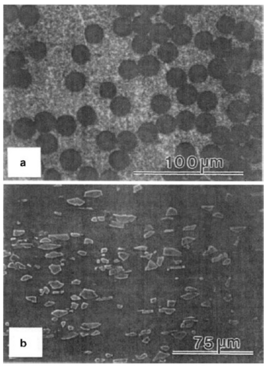
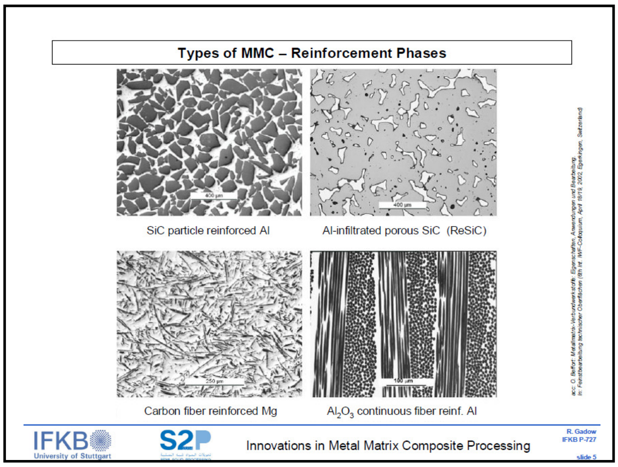


Fig. 6.1 (a) Transverse cross-section of continuous alumina fiber/magnesium alloy composite. (b) Typical microstructure of a silicon carbide particle/aluminum alloy composite. Note the angular nature of SiC particles and alignment of particles along the long axis


Types of MMC – Reinforcement Phases
SiC particle reinforced Al
Al-infiltrated porous SiC (ReSiC)
Carbon fiber reinforced Mg
Al2O3 continuous fiber reinf. Al
IFKB University of Stuttgart
S2P
Innovations in Metal Matrix Composite Processing
R. Gadow
IFKB P-727
slide 5


MMC Applications in Automotive Industry: mainly Particle Reinforcement
Light metal crankcase; particle reinforcement of cylinders and bedplates
Heterogeneous solutions
cast iron & AlSi bushings (Silitec®)
Monolithic solutions
AlSi17Cu4Mg (Alusil®)
hypereutectic alloy
Quasi-monolithic solutions
preform infiltration (Lokasil®)
& various coatings
Nikasil®:
galvanic Ni + SiC particles
Lokasil I®: squeeze casting
of Si cylinder liner preform
Lokasil® bedplate (particle
or fiber/particle preform)
Reinforced piston rods and piston; short fiber or particle reinforcements
Piston rod,
ZC71/SiC/12p;
microstructure after
forging
Process: stir casting of billets,
hot extrusion and die-forging.
acc: Mahle AG, Stuttgart
Piston, 20 %vol. Saffil
(δ-Al2O3) short fiber
reinforced aluminium
(Al Si12CuMgNi (KS1275) / Saffil / 20sf / squeeze casting)
IFKB University of Stuttgart
S2P
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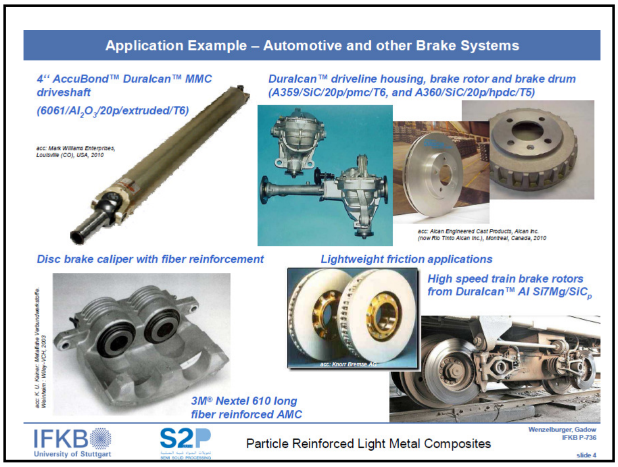
Application Example – Automotive and other Brake Systems
4" AccuBond™ Duralcan™ MMC
driveshaft
(6061/Al2O3/20p/extruded/T6)
Duralcan™ driveline housing, brake rotor and brake drum
(A359/SiC/20p/pmc/T6, and A360/SiC/20p/hpdc/T6)
Disc brake caliper with fiber reinforcement
Lightweight friction applications
High speed train brake rotors
from Duralcan™ Al Si7Mg/SiCp
3M® Nextel 610 long
fiber reinforced AMC
IFKB University of Stuttgart
S2P
Particle Reinforced Light Metal Composites
Wenzelburger, Gadow
IFKB P-736
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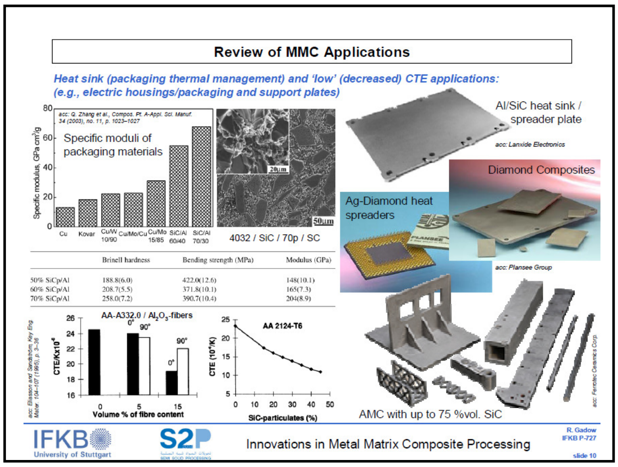
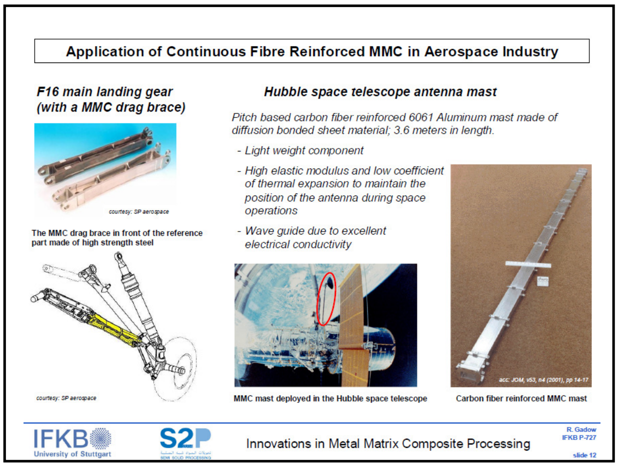




Processing

- 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

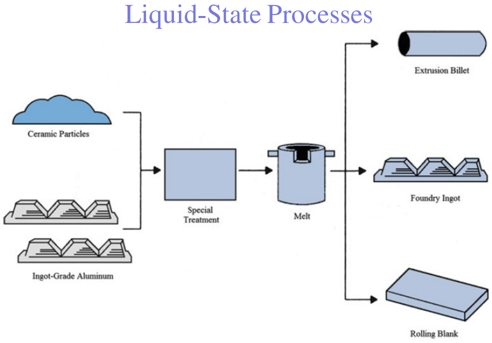


Fig. 6.2 Schematic of the Duralcan process

Composite Materials, 2016, BN, IUT, Iran

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.

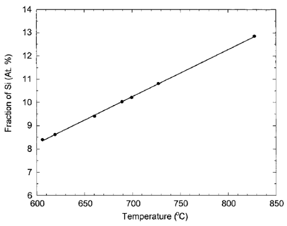


Fig. 4.2 Fraction of Si, at a given temperature, required to prevent formation of Al_4C_3 in an Al-Si/SiC composite (after Lloyd, 1997).

Composite Materials, 2016, BN, IUT, Iran

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,

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

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.

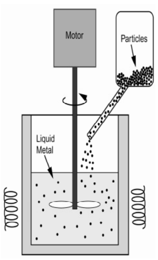
- SiC density= 3.2 g/cm^3, Al density= 2.7 g/cm^3
- Stirring: Mechanical, induction, ultrasonic vibration, …

- 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 %

Composite Materials, 2016, BN, IUT, Iran

Liquid-State Processes

Sedimentation of particles

- $\rho_{particle} > \rho_{Matrix}$ ⇒ 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)
ρ_p = mass density of the particles (kg/m^3)
μ = dynamic viscosity (kg /m.s)
g = gravitational acceleration (m/s^2)
ρ_f = mass density of the fluid (kg/m^3)
R = particle radius

✓ **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

Composite Materials, 2016, BN, IUT, Iran

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.

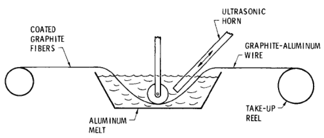


Figure 7.12 Ultrasonic vibration of an aluminum melt to assist the infiltration of a bundle of coated carbon fibers. From Ref. 14. (Reprinted by courtesy of Marcel Dekker, Inc.)

Composite Materials, 2016, BN, IUT, Iran

Liquid-State Processes

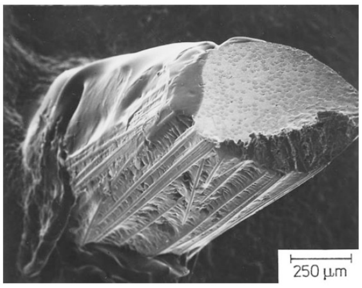
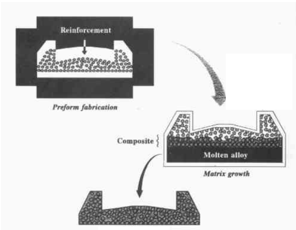


Fig. 6.3 A silicon carbide fiber/aluminum wire preform. SiC fibers can be seen in the transverse section as well as along the length the wire preform

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.



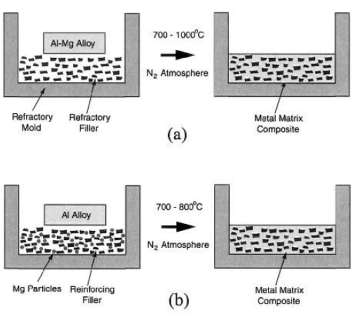
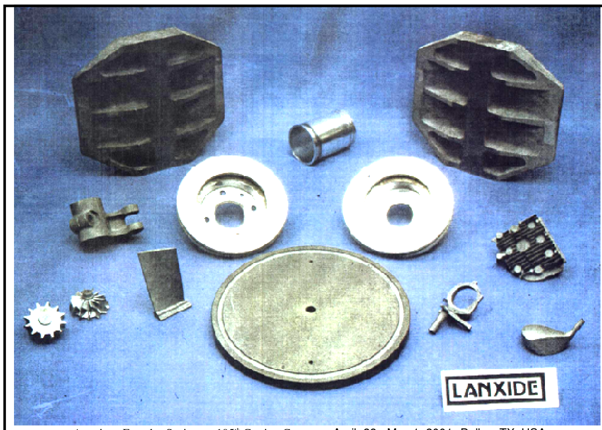


Fig. 4.8 Pressureless infiltration of MMCs: (a) Alloy matrix infiltration of particulate preform and (b) pure matrix infiltration of metallic alloy particle and ceramic particulate preform.

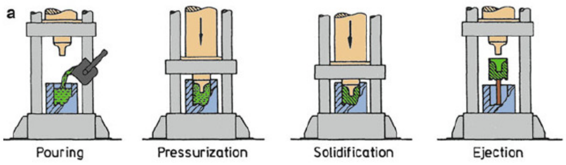


American Foundry Society · 105th Casting Congress, April 28 - May 1, 2001--Dallas, TX, USA

Liquid-State Processes

✓ **Squeeze casting / pressure infiltration:**

- **Squeeze casting of a composite slurry**
  - A composite slurry prepared by other casting methods, e.g. vortex method, is solidified under a mechanically applied pressure



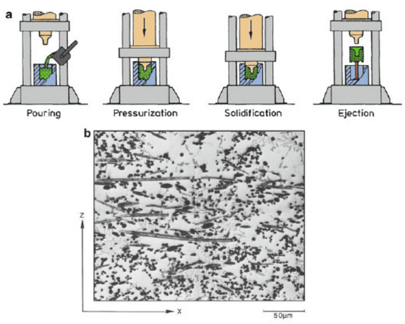
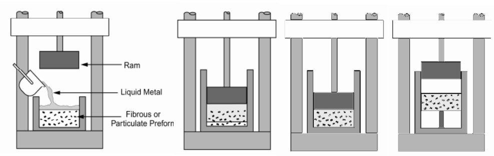


Fig. 6.5 (a) Squeeze casting technique of making a metal matrix composite. (b) The microstructure of Saffil alumina fiber/aluminum matrix composite made by squeeze casting. [Courtesy of G. Eggeler]

Liquid-State Processes

- **Squeeze casting/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

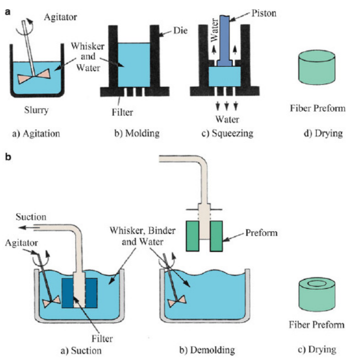
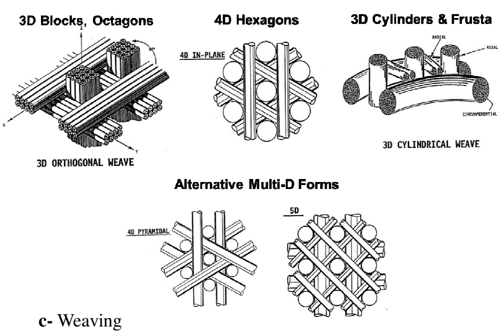


Fig. 6.4 (a) Press forming of a preform. (b) Suction forming of a preform

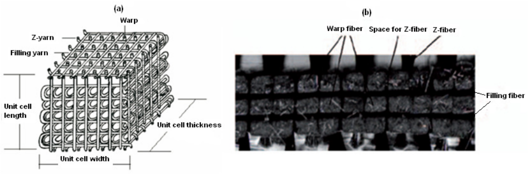
Liquid-State Processes

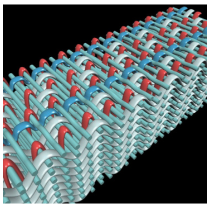
Structural Composite Architectural Forms



c- Weaving

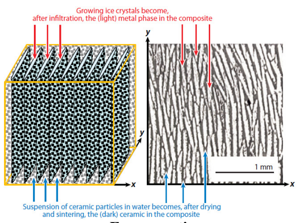
Liquid-State Processes





Liquid-State Processes

d- Pyrolysis of a polymeric preform
e- Ceramic coating of a polymeric preform followed by sintering
f- Freeze-casting
-…



Freeze-casting

- (Left) Directional growth of Ice crystals in a slurry of water and high volume fraction of fine ceramic particles
- The growing ice crystals push the ceramic into the grain boundaries.
- After drying and sintering, a porous ceramic preform is obtained.

- (Right) A freeze-cast Al-12Si-Al_2O_3 composite produced by squeeze casting

Liquid-State Processes

Permeability of porous medium by a fluid

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

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

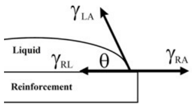
- *J*: Volume current density (i.e., volume/area×time) of the fluid
- *k*: The permeability of a porous medium
- η: The fluid viscosity
- ∇P: The pressure gradient responsible for the fluid flow

- **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 $\sigma_{RA} > \sigma_{RL} + \sigma_{LA}.Cos\theta \rightarrow$ **Spontaneous infiltration** of molten metal into the preform!
- If $\sigma_{RA} < \sigma_{RL} + \sigma_{LA}.Cos\theta$, 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

$$P \propto S_f (\sigma_{RL} + \sigma_{LA}.Cos\theta - \sigma_{RA})$$

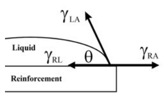
or $$P \propto -S_f (\sigma_{RA} - \sigma_{RL} - \sigma_{LA}.Cos\theta)$$

  - S_f: The specific surface area of the preform (interface per unit volume of the matrix)
- If melt is to be forced through a channel of width r:

$$\Rightarrow P \propto -S_f (\sigma_{RA} - \sigma_{RL} - \sigma_{LA}.Cos\theta)/r$$

Liquid-State Processes

$$P \propto -S_f (\sigma_{RA} - \sigma_{RL} - \sigma_{LA}.Cos\theta)/r$$



- Infiltration is improved by increasing σ_{RA} and decreasing σ_{RL}.
- In wetting systems (θ < 90°), infiltration is improved by increasing S_f and decreasing *r*.
- In non-wetting systems (θ > 90°), infiltration is improved by reducing S_f and increasing *r*.
- S_f and *r* are dependent on volume fraction and size of the reinforcements.

Liquid-State Processes

- 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.
- 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

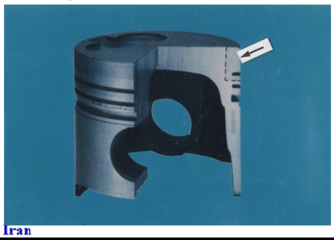
Liquid-State Processes

- 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

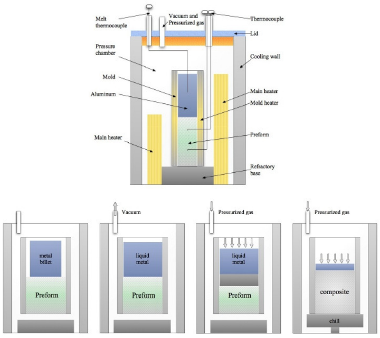
Pressure Gas Infiltration of a preform

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

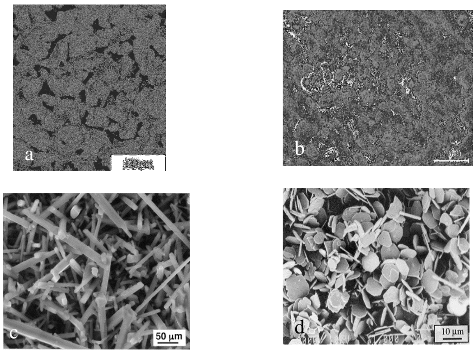
Process involves:

- 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.

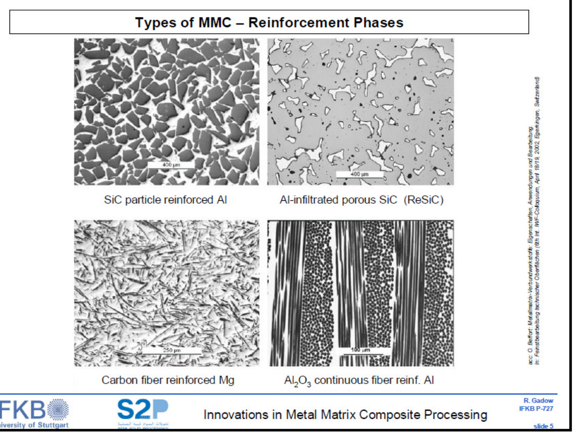
Liquid-State Processes



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



Liquid-State Processes

Centrifugal Casting

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

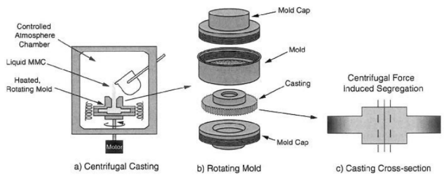
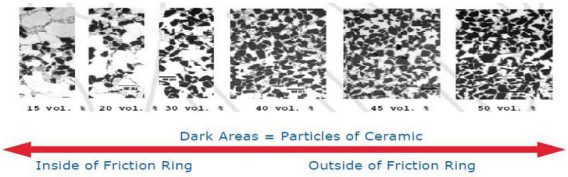


Fig. 4.4 (a) Schematic of centrifugal casting process, (b) rotating mold, and (c) cross-section of finished casting with intentionally-segregated reinforcement.

Liquid-State Processes

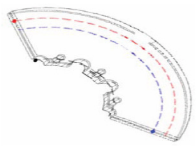
Brake rotors

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



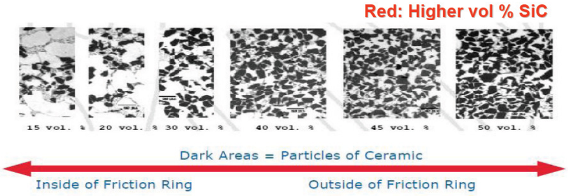
Liquid-State Processes

- **Motor cycle brake rotor**



Blue: Lower vol % SiC

Red: Higher vol % SiC



Liquid-State Processes

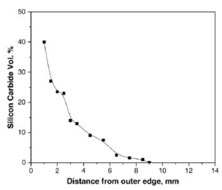


Fig. 7 – Graded distribution SiC particle from the outer periphery of the Al(2124)-SiC centrifugal cast ring.

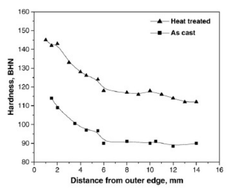


Fig. 8 – Variation in hardness from outer edge of as-cast and heat treated Al(2124)-SiC functionally graded composites.

T.P.D. Rajan, R.M. Pillai, B.C. Pai , M A T E R I A L S C H A R A C T E R I Z A T I O N 6 1 (2 0 1 0) 9 2 3 – 9 2 8

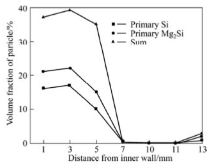


Fig. 3 Volume fraction of reinforced particles at different positions

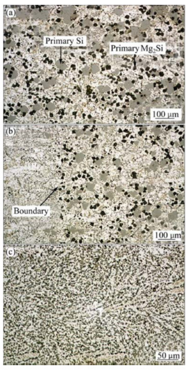


Fig. 2 Microstructures of Mg_2Si/Si/Al gradient composites at different locations: (a) Particle-rich layer; (b) Transition zone; (c) Particle-free layer

B. Li, , et al., Trans. Nonferrous Met. Soc. China 23(2013) 923-930.

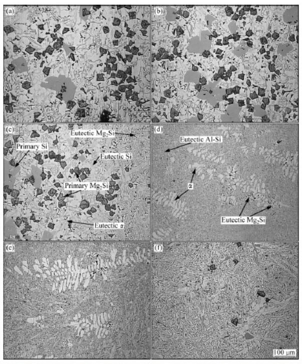
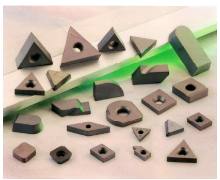


Fig.6 SEM images of Al-19Si-5Mg tube in Fig.2(b): (a) 1−3 mm; (b) 3−5 mm; (c) 5−8 mm; (d) 8−10 mm; (e) 10−14 mm; (f) 14−15 mm)

Zhai Y., et al., Trans. Nonferrous Met. Soc. China 20(2010) 361-370.

Liquid-State Processes

Processing of WC/Co Composites



- Cemented carbides = WC/Co MMC
- Liquid cobalt wets WC particles very easily (θ=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

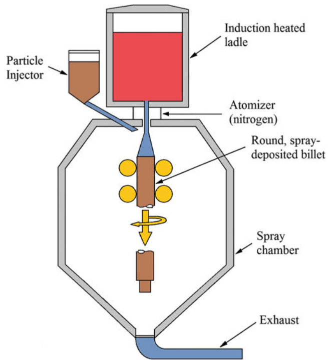
➢ Pressureless liquid phase sintering

- 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.

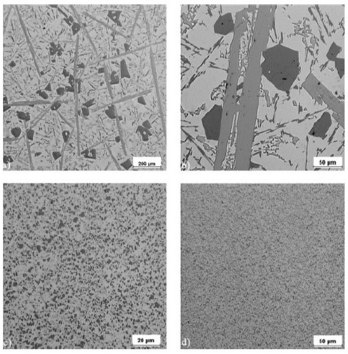
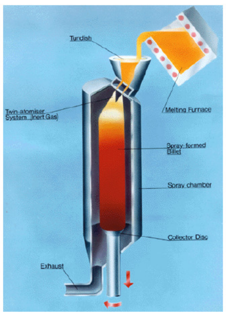
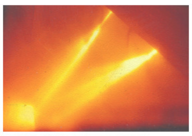


Fig. 11.7 Microstructure of alloy AlSi20Fe5Ni2, "as cast" and "as sprayed". (a) as cast 50×; (b) as cast 200×; (c) spray formed 200×; (d) spray formed 500×.

Spray Forming



The Osprey vertical billet process



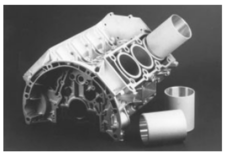
Steel billet being horizontally spray formed by twin atomization

Al/Si spray-formed billet (300 mm Ø, 2.5 m length) (courtesy of Peak)

acc: Alan Leatham (Osprey Metals Ltd.), JOM, April 1999 (vol. 51, no. 4), presented as JOM-e

Liquid-State Processes

- Extremely short flight times →formation of deleterious reaction products avoided
- High production rate: 6-10 kg/min



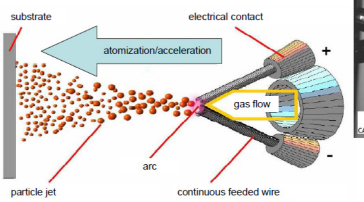
High pressure die cast crankcase with indirect extruded cylinder liners of the spray formed alloy AlSi25Cu4Mg.

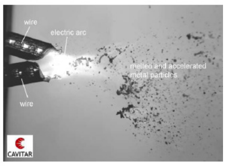
- Great flexibility in making different types of composites, e.g.
  - Making in situ laminates using two sprayers
  - Selective reinforcement
  - Functionally graded Materials (FMGs) are possible

Composite Materials, 2016, BN, IUT, Iran

Thermal Spraying of Matrix Alloys

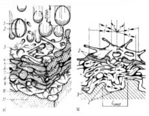
Arc wire spray torch (schematic):



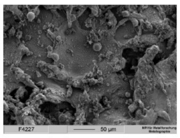


Twin-wire arc spraying of aluminum

Energy source:	electric arc
Max. process temp.:	4000 °C
Materials:	metals, alloys
Particle velocity:	150 m/s
Deposition rate:	20 - 300 kg/h



acc: Pursche, Oberflächenschutz vor Verschleiß, 1990



SEM of an AlSi5 coating surface by twin-wire arc spraying

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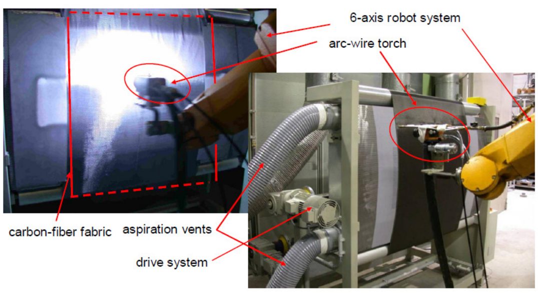
Thermal Spray Manufacturing of Pre-Impregnated Material (Prepregs)

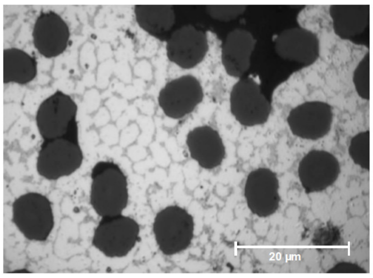
Continuous coating of fiber fabrics from coil to coil up to 1500 mm in width



IFKB University of Stuttgart | S2P | Innovations in Metal Matrix Composite Processing | R. Gadow IFKB P-727 | slide 35

Microstructure of Thermal Spray / Reheated Aluminum

Arc wire sprayed AlSi6 coated carbon fibers



SEM micrograph of a cross section of coated carbon fiber fabric after heating

Matrix Application by Thermal Spray (TS) Processes

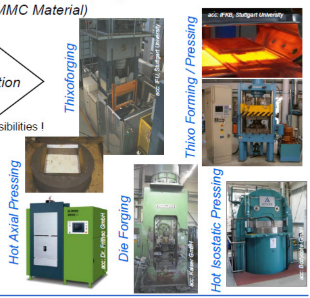
Reduced Chemical Reaction at Fiber/Matrix Interfaces during Application

—

Separation of Liquid Metal Compounding (Prepreg) and Densification (Final MMC Material)

Densification

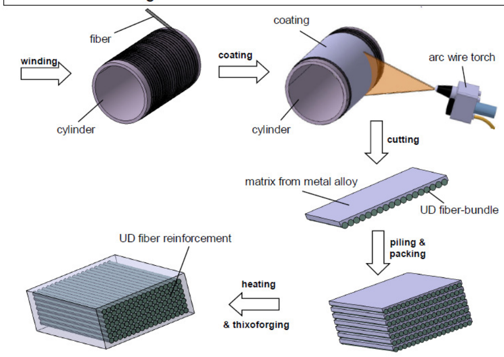
Various possibilities !

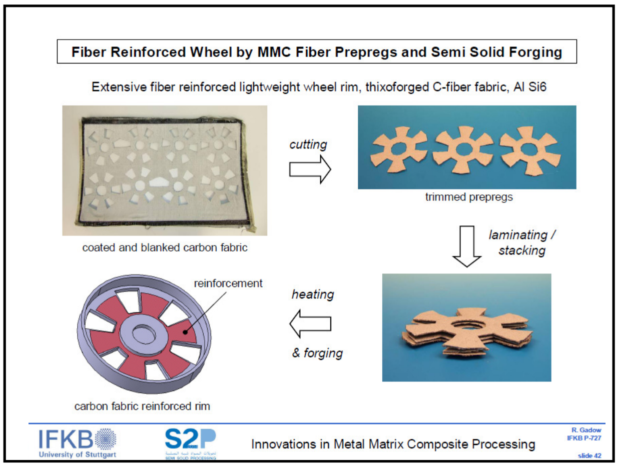


C-fiber fabric / Al Si5-Prepreg

- pre-impregnated, semi-finished material, TS coated (twin-wire arc spraying) from both sides for residual stress balancing

Manufacturing of UD Fiber Reinforced MMC – Process Chain




Fiber Reinforced Wheel by MMC Fiber Prepregs and Semi Solid Forging
Extensive fiber reinforced lightweight wheel rim, thixoforged C-fiber fabric, Al Si6
cutting
coated and blanked carbon fabric
trimmed prepregs
laminating / stacking
reinforcement
heating
& forging
carbon fabric reinforced rim
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S2P
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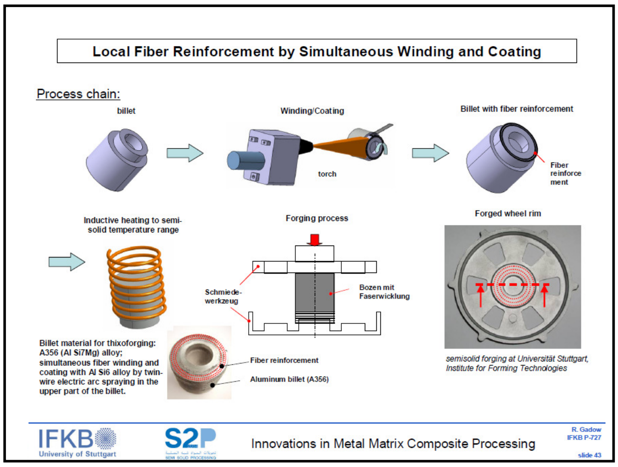
slide 42


Local Fiber Reinforcement by Simultaneous Winding and Coating
Process chain:
billet
Winding/Coating
torch
Billet with fiber reinforcement
Fiber reinforce ment
Inductive heating to semi-solid temperature range
Forging process
Schmiede-werkzeug
Bozen mit Faserwicklung
Forged wheel rim
Billet material for thixoforging: A356 (Al Si7Mg) alloy; simultaneous fiber winding and coating with Al Si6 alloy by twin-wire electric arc spraying in the upper part of the billet.
Fiber reinforcement
Aluminum billet (A356)
semisolid forging at Universität Stuttgart, Institute for Forming Technologies
IFKB
University of Stuttgart
S2P
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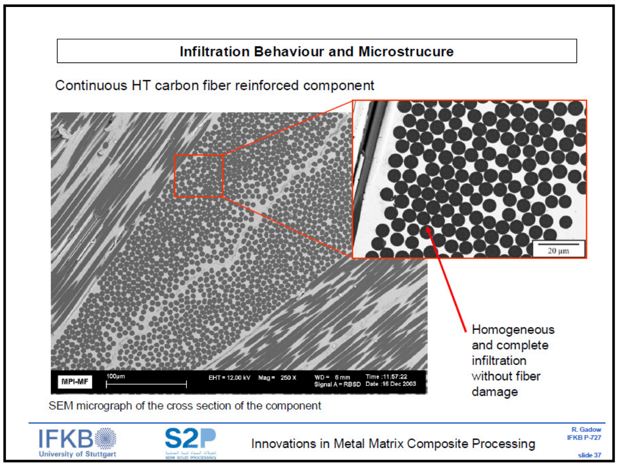
slide 43


Infiltration Behaviour and Microstrucure
Continuous HT carbon fiber reinforced component
20 µm
Homogeneous and complete infiltration without fiber damage
SEM micrograph of the cross section of the component
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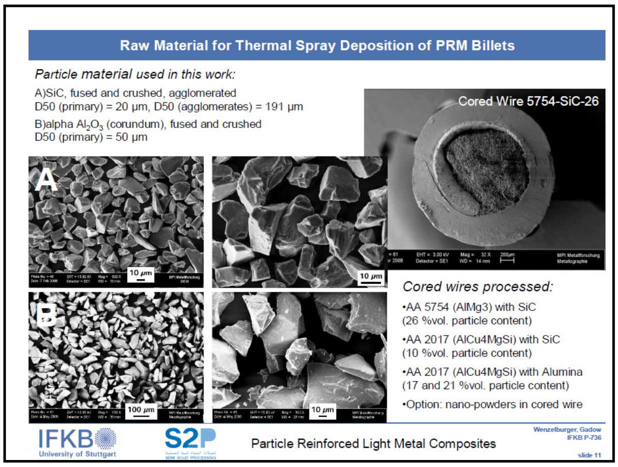
slide 37


Raw Material for Thermal Spray Deposition of PRM Billets
Particle material used in this work:
A)SiC, fused and crushed, agglomerated
D50 (primary) = 20 µm, D50 (agglomerates) = 191 µm
B)alpha Al2O3 (corundum), fused and crushed
D50 (primary) = 50 µm
Cored Wire 5754-SiC-26
A
B
10 µm
10 µm
100 µm
10 µm
Cored wires processed:
•AA 5754 (AlMg3) with SiC
(26 %vol. particle content)
•AA 2017 (AlCu4MgSi) with SiC
(10 %vol. particle content)
•AA 2017 (AlCu4MgSi) with Alumina
(17 and 21 %vol. particle content)
•Option: nano-powders in cored wire
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Particle Reinforced Light Metal Composites
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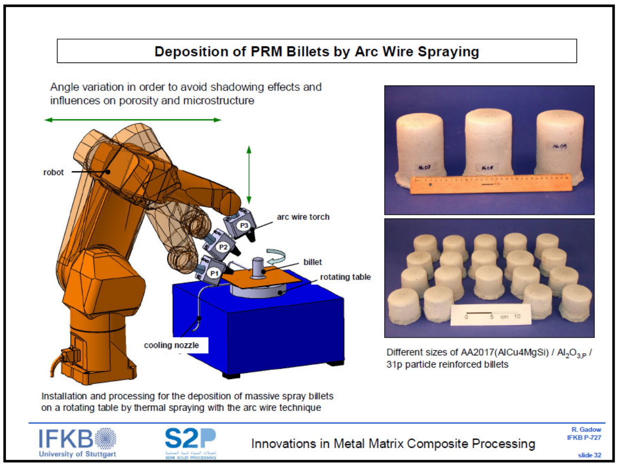
slide 11


Deposition of PRM Billets by Arc Wire Spraying
Angle variation in order to avoid shadowing effects and
influences on porosity and microstructure
robot
arc wire torch
billet
rotating table
cooling nozzle
P1
P2
P3
Different sizes of AA2017(AlCu4MgSi) / Al2O3,P /
31p particle reinforced billets
Installation and processing for the deposition of massive spray billets
on a rotating table by thermal spraying with the arc wire technique
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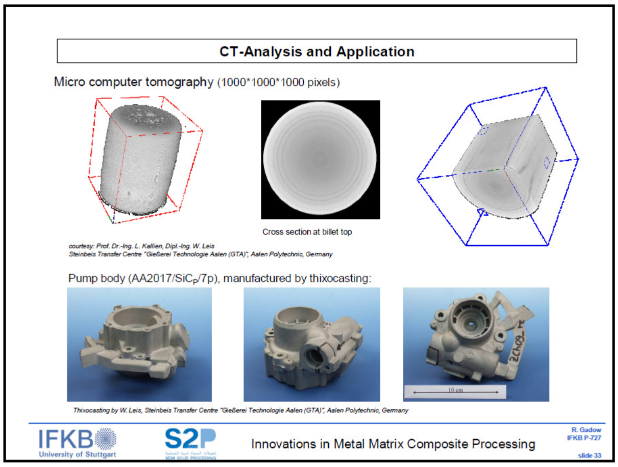
slide 32


CT-Analysis and Application
Micro computer tomography (1000*1000*1000 pixels)
Cross section at billet top
courtesy: Prof. Dr.-Ing. L. Kallien, Dipl.-Ing. W. Leis
Steinbeis Transfer Centre "Gießerei Technologie Aalen (GTA)", Aalen Polytechnic, Germany
Pump body (AA2017/SiCp/7p), manufactured by thixocasting:
Thixocasting by W. Leis, Steinbeis Transfer Centre "Gießerei Technologie Aalen (GTA)", Aalen Polytechnic, Germany
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Innovations in Metal Matrix Composite Processing
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slide 33

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.
- Fineness of distribution of the reinforcement phase is controlled by the solidification rate.

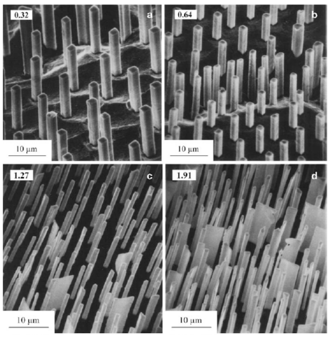

Fig. 6.9 Transverse sections of in situ composites obtained from a eutectic at different solidification rates indicated in *left-hand top* corners (cm/h). The nickel alloy matrix has been etched away to reveal the TaC fibers. [From Walter (1982), used with permission]

Liquid-State Processes

Table 6.2 Some important in situ composite systems

System	Carbide (vol. %)	T_E[a] (°C)
Co–NbC	12	1,365
Co–TiC	16	1,360
Co–TaC	10	1,402
Ni–HfC	15–28	1,260
Ni–NbC	11	1,330
Ni–TiC	7.5	1,307

[a] T_E is the eutectic temperature

Add more of desplacive reactions.

•**XD™/ SHS** (self-propagating high-temperature synthesis) process: An exothermic reaction between two components is used to produce a third component.
A master alloy with high vol% of reinforcement is produced which can be mixed and remelted with a base alloy to produce a desirable amount of particle reinforcement, for example SiC or TiB_2 in an aluminum, nickel, or intermetallic matrix.

Solid-State Processes

Diffusion bonding

- Used to join similar or dissimilar metals
- Stacking in a predetermined order 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