Composite Materials

Processing and applications of MMCs

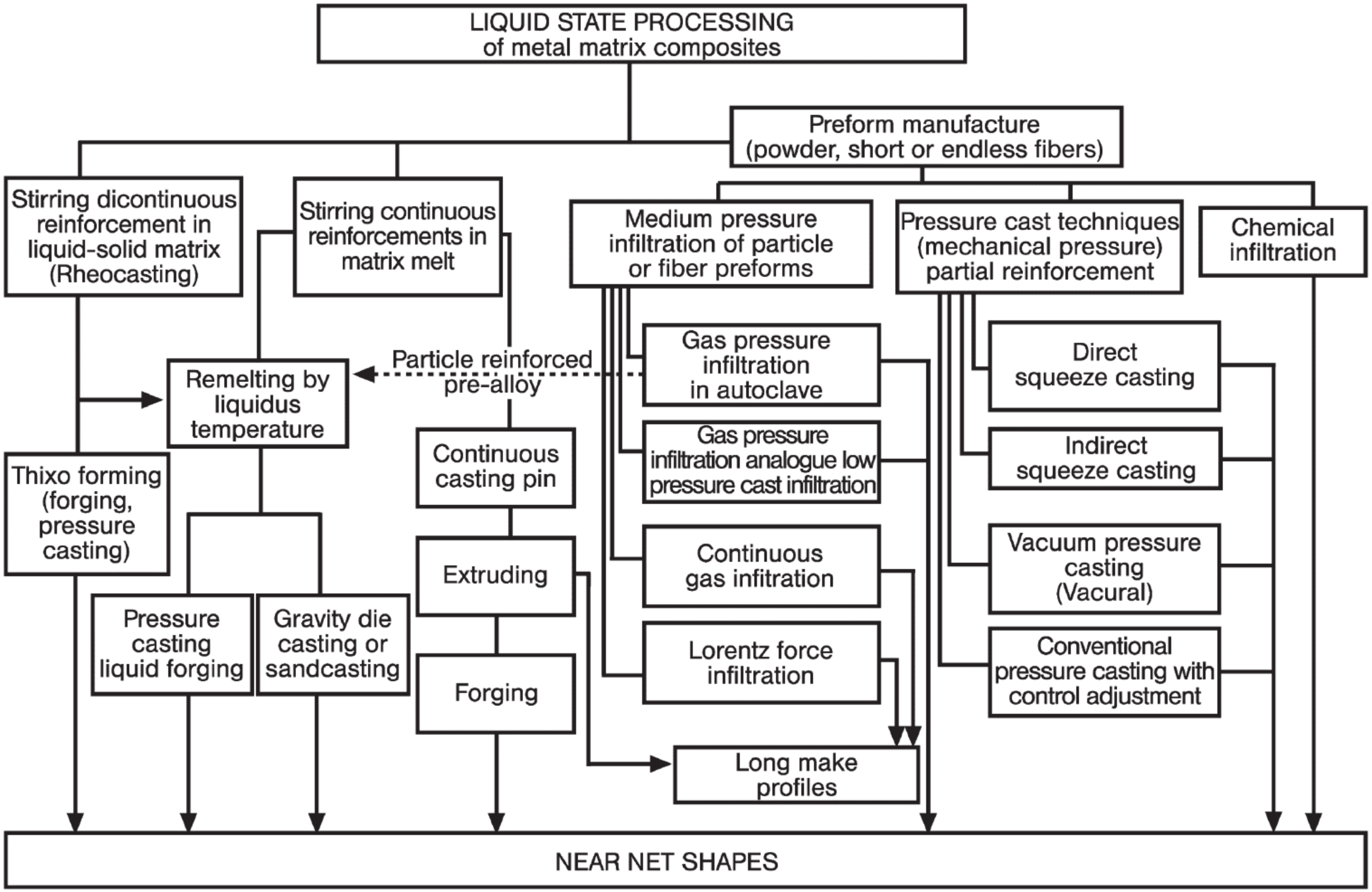
Manufacturing

The mechanical properties and the microstructure of MMCs depend strongly on the manufacturing method

In general, MMC components with dimensions close to the final product are desired for cost efficiency. Mechanical finishing is done when needed similar to metal processing but with harder tools

The following manufacturing processes are possible:

- *Melt processing*
- *Further processing of melt processed material by thixocasting, extrusion, forging, cold forming, super plastic forming*
- *Powder processing*
- *Hot isostatic pressing of powder and fiber mixtures*
- *Joining and welding of semi-manufactured parts*



LIQUID STATE PROCESSING
of metal matrix composites
Preform manufacture
(powder, short or endless fibers)
Stirring dicontinuous reinforcement in liquid-solid matrix (Rheocasting)
Stirring continuous reinforcements in matrix melt
Medium pressure infiltration of particle or fiber preforms
Pressure cast techniques (mechanical pressure) partial reinforcement
Chemical infiltration
Particle reinforced pre-alloy
Remelting by liquidus temperature
Gas pressure infiltration in autoclave
Direct squeeze casting
Gas pressure infiltration analogue low pressure cast infiltration
Indirect squeeze casting
Thixo forming (forging, pressure casting)
Continuous casting pin
Continuous gas infitration
Vacuum pressure casting (Vacural)
Extruding
Pressure casting liquid forging
Gravity die casting or sandcasting
Lorentz force infiltration
Conventional pressure casting with control adjustment
Forging
Long make profiles
NEAR NET SHAPES

Manufacturing

Melt processing methods are of technical importance compared to other MMC manufacturing methods because they are well proven casting processes used also for metal processing

- *Infiltration of short fiber, particle or hybrid preforms by* ***squeeze casting****, vacuum infiltration or* ***pressure infiltration***
- *Reaction infiltration of fiber or particle preforms*
- ***Processing of the material by stirring the particles in the melt****, followed by sand casting, permanent mold casting or high pressure die casting*

Melt stirring

Melt stirring is basically used to stir particles into an alloy melt

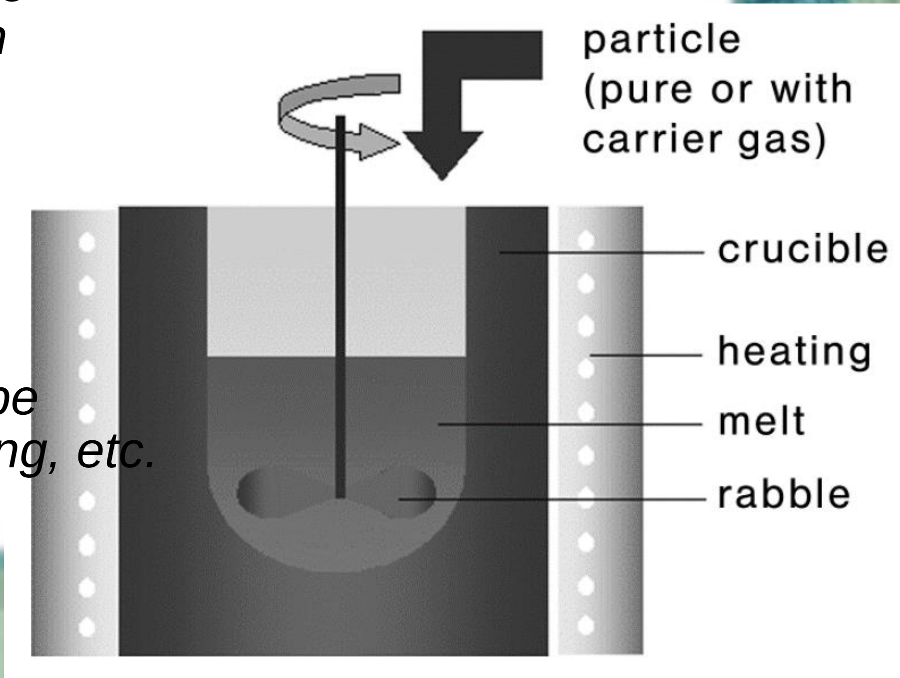
The particles often tend to form agglomerates which can only be dispersed by intense stirring

It is important to avoid gas access into the melt since it leads to unwanted porosities and reactions

There is also the risk of reaction of the particles with the melt and dissolution due to excess stirring

However reactivity of stirred particles is less critical than fibers because of the lower surface to volume ratio of spherical particles

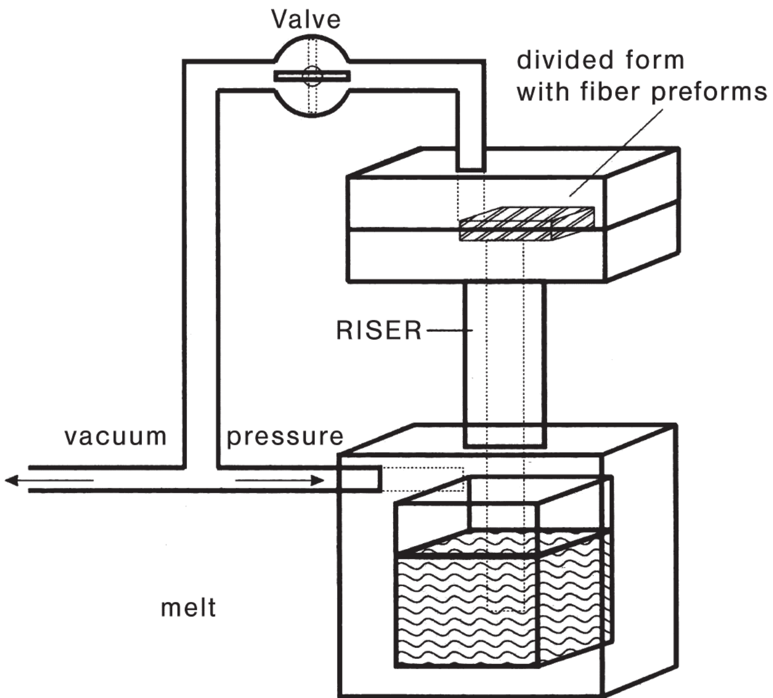
The melt can be directly cast or can be further processed with squeeze casting, etc.



Pressure infiltration

In gas pressure infiltration the melt infiltrates the preform with a gas applied from the outside

A gas that is inert with respect to the matrix is used to pressurize the melt in a suitable pressure vessel



1. *The warmed up preform is dipped into the melt and then the gas pressure is applied to the surface of the melt, leading to infiltration. (Higher the volume fraction of the reinforcement, higher the gas pressure)*
2. *The molten bath is pressed to the preform by the applied gas pressure using a standpipe and infiltration occurs.*

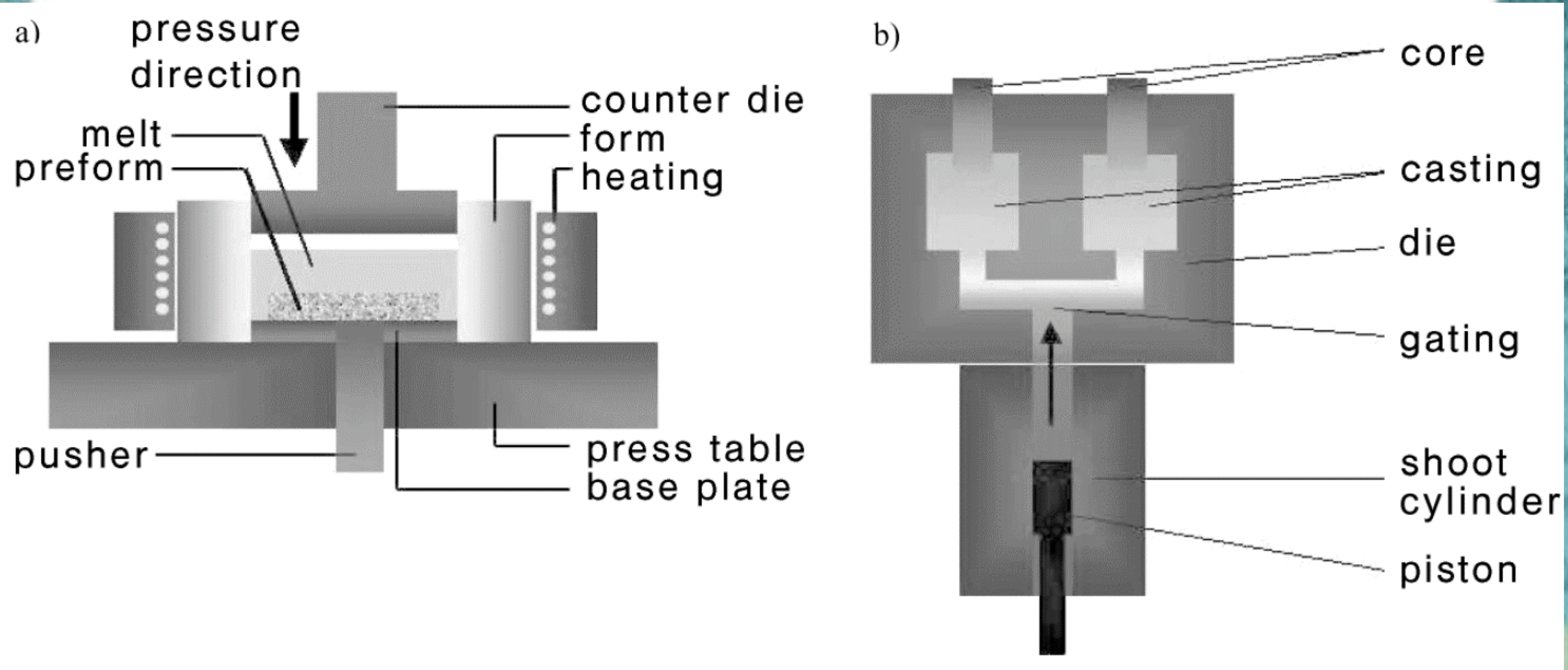
The process eliminates pores in the melt so that completely dense parts are obtained

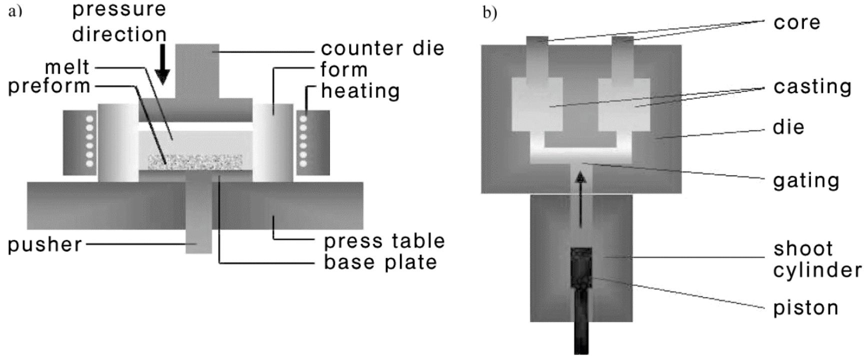
Another advantage is that the reaction time is relatively short and more reactive materials can be used as in the preform

Squeeze casting

Squeeze casting is the most common manufacturing process for MMCs

A mold is filled slowly and metal solidifies under very high pressure, leading to a fine-grained structure





Squeeze casting

- *Direct squeeze casting enables application of the pressure directly to the melt for the infiltration of the preforms. (The die is a part of the mold)*

In this type of squeeze casting there is no gate so that the volume of the melt must be determined exactly

- *In indirect squeeze casting the melt is pressed into the preform via a gate system*

In squeeze casting a two stage process is used:

1. The melt is pressed into the preform at low pressure so that damage to the preform by fast infiltration is avoided

2. The melt solidifies under high pressure so that a fine grain structure is obtained

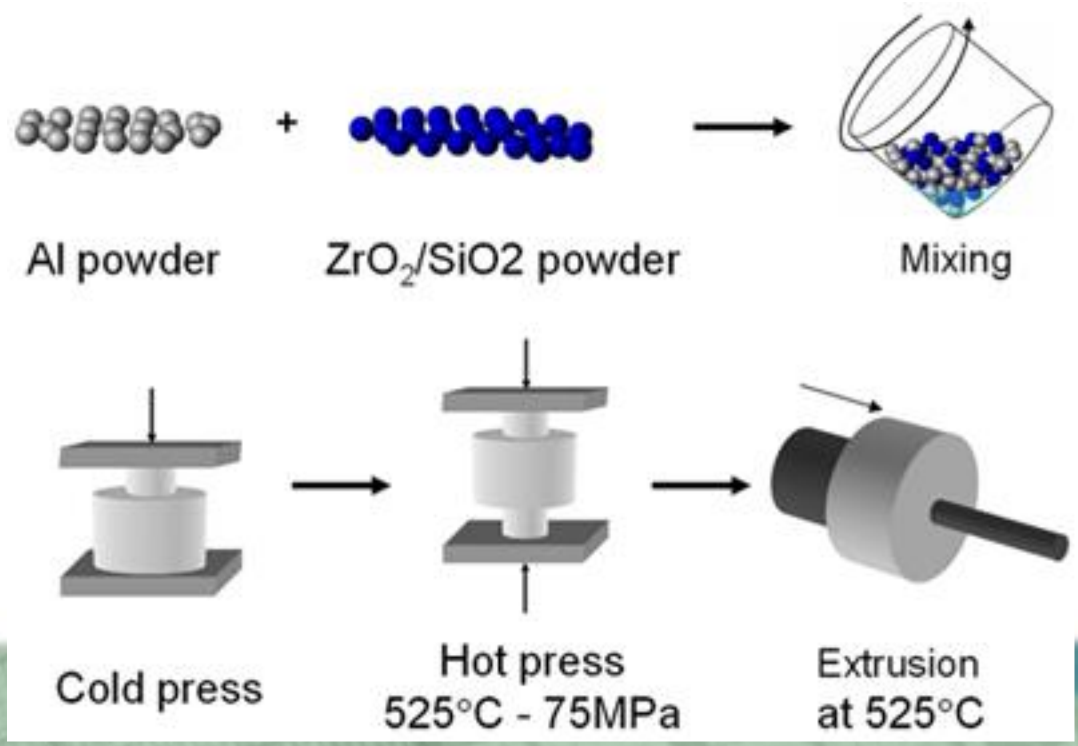
Especially difficultly shaped components are manufactured and partial reinforcement (strengthening the areas that are exposed to higher stresses) is possible

Manufacturing

Powder metallurgical processes

Pressing and sintering/forging of composite powder mixtures

Extrusion or forging of metal powder particle mixtures



Manufacturing

Upon addition of a particle or fiber reinforcement to a metal, the extent of increase in the mechanical properties depends on the manufacturing process as well as the reinforcement content

In melting metallurgically manufactured materials and mixing in particles, the upper limit of the particle addition is approximately 20 vol%. The mechanical properties reach maximum at this limit

Higher particle contents result in a composite with a more ceramic character, becoming susceptible to brittle failure. Still the thermal expansion coefficient of these composites are very low

Tab. 1.7 Selected properties of typical aluminum cast composites, processed by ingot-, die cast or reaction infiltration, Manufacturers instruction after [11, 12, 16]. (T6 = solution annealed and artificially aged; T5 = artificially aged; *after ASTM G-77: Cast iron 0.066 mm^3; **CTE = thermal expansion coefficient, (a) after ASTM E-399 and B-645; (b) after ASTM E-23).

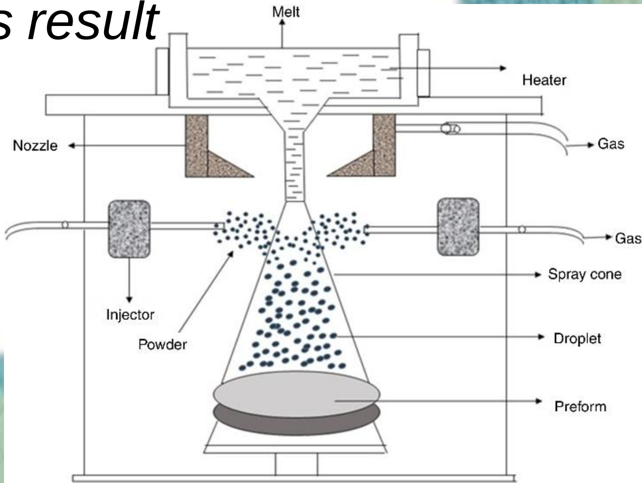
Material		*Yield stress (MPa)*	*Tensile strength (MPa)*	*Ultimate strain (%)*	*Young's modulus (GPa)*	*(a) Fracture toughness (b) Impact strength*	*Wear* Volume decrease (mm^3)*	*Thermal conductivity 22 °C (cal cm^{-1} s^{-1} K^{-1})*	*CTE** 50–100 °C (10^{-6} K^{-1})*
Name	*Composition*								
Gravity die casting (Chill casting)						(a) (MPa $m^{1/2}$)			
A356-T6	AlSi7g	200	276	6.0	75.2	17.4	0.18	0.360	21.4
F3S.10S-T6	AlSi9Mg10SiC	303	338	1.2	86.9	17.4			20.7
F3S.20S-T6	AlSi9Mg20SiC	338	359	0.4	98.6	15.9	0.02	0.442	17.5
F3K.10S-T6	AlSi10CuMgNi10SiC	359	372	0.3	87.6				20.2
F3K.20S-T6	AlSi10CuMgNi20SiC	372	372	0.0	101			0.346	17.8
Die casting						(b) (J)			
A390		241	283	3.5	71.0	1.4	0.18	0.360	21.4
F3D.10S-T5	AlSi10CuMnNi10SiC	331	372	1.2	93.8	1.4		0.296	19.3
F3D.20S-T5	AlSi10CuMnNi20SiC	400	400	0.0	113.8	0.7	0.018	0.344	16.9
F3N.10S-T5	AlSi10CuMnMg10SiC	317	352	0.5	91.0	1.4		0.384	21.4
F3N.20S-T5	AlSi10CuMnMg20SiC	338	365	0.3	108.2	0.7	0.018	0.401	16.6
Reaction infiltration		Flexural strength (MPa)		Density (g cm^{-3})		(a) (MPa $m^{1/2}$)			
MCX-693™	Al+55-70% SiC	300	2.98	255	9.0		0.430	6.4	
MCX-724™	Al+55-70% SiC	350	2.94	226	9.4		0.394	7.2	
MCX-736™	Al+55-70% SiC	330	2.96	225	9.5		0.382	7.3	

Manufacturing

- *The limit for the particle content is about 13-15% for spray formed materials*

This low content limits the mechanical properties of the composite but the use of special alloys with lithium addition can lead to high specific properties.

- *The particle content can be increased to over 40% in powder metallurgical materials processed by extrusion from powder mixtures. Very high strength and modulus and low expansion coefficient and fracture toughness result*



Tab. 1.8 Properties of aluminum wrought alloy composites. Manufacturers instruction after [11, 12, 18–20]. (T6 = solution annealed and artificially aged; *after ASTM G-77: Cast iron 0.066 mm^3; **CTE = thermal expansion coefficient).

Material		*Yield stress (MPa)*	*Tensile strength (MPa)*	*Ultimate strain (%)*	*Young's modulus (GPa)*	*Fracture toughness ($MPa\ m^{1/2}$) ASTM E-399*	*Wear* volume decrease (mm^3)*	*Thermal conductivity 22°C ($cal\ cm^{-1}\ s^{-1}\ K^{-1}$)*	*CTE** 50–100°C ($10^{-6}\ K^{-1}$)*
Name	*Composition*								
Cast prematerial (extruded or forged)									
6061 -T6	AlMg1SiCu	355	375	13	75	30	10	0.408	23.4
6061 -T6	+ 10 % Al_2O_3	335	385	7	83	24	0.04	0.384	20.9
6061 -T6	+ 15 % Al_2O_3	340	385	5	88	22	0.02	0.336	19.8
6061 -T6	+ 20 % Al_2O_3	365	405	3	95	21	0.015		
Powder metallurgically processed prematerial (extruded)									
6061 -T6	AlMg1SiCu	276	310	15	69.0				23.0
6061 -T6	+ 20 % SiC	397	448	4.1	103.4				15.3
6061 -T6	+ 30 % SiC	407	496	3.0	120.7				13.8
7090-T6		586	627	10.0	73.8				
7090-T6	+ 30 % SiC	676	759	1.2	124.1				
6092-T6	AlMg1Cu1Si17.5SiC	448	510	8.0	103.0				
6092-T6	AlMg1Cu1Si25SiC	530	565	4.0	117.0				
Spray formed material (extruded)									
6061-T6	+ 15 % Al_2O_3	317	359	5	87.6				
2618-T6	+ 13 % SiC	333	450		89.0				19.0
8090-T6	AlCuMgLi	480	550		79.5				22.9
8090-T6	+ 12 % SiC	486	529		100.1				19.3

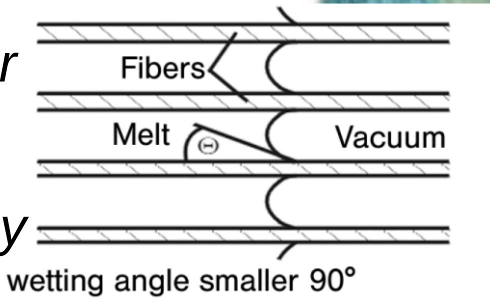
Infiltration of preforms by metal melt

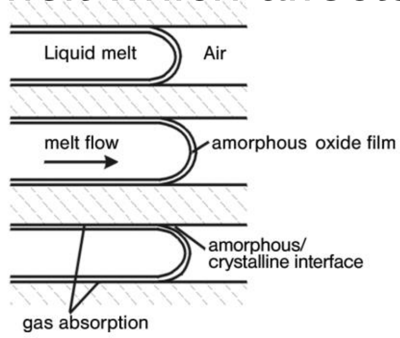
Process parameters for infiltration are pressure applied to the melt, surface energies of the phases (wetting angle), specific surface area of the preform, viscosity of the melt (temperature)

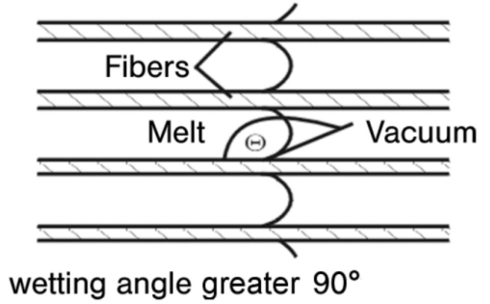
In simple wetting of fibers by metal melt at equilibrium, it is easier to combine the phases when the wetting angle is small and a capillary effect helps wetting

At large wetting angles capillary effect does not occur

Also at large angles reaction between the melt and the atmosphere is promoted so that an oxide film may form on the metal melt which affects the wetting behavior







Infiltration of preforms by metal melt

The effect of wetting on the infiltration rate is limited in industrial processes like squeeze casting because the kinetics are affected mainly by the applied pressure or the flow rate of the melt in the preform

There are three steps of infiltration:

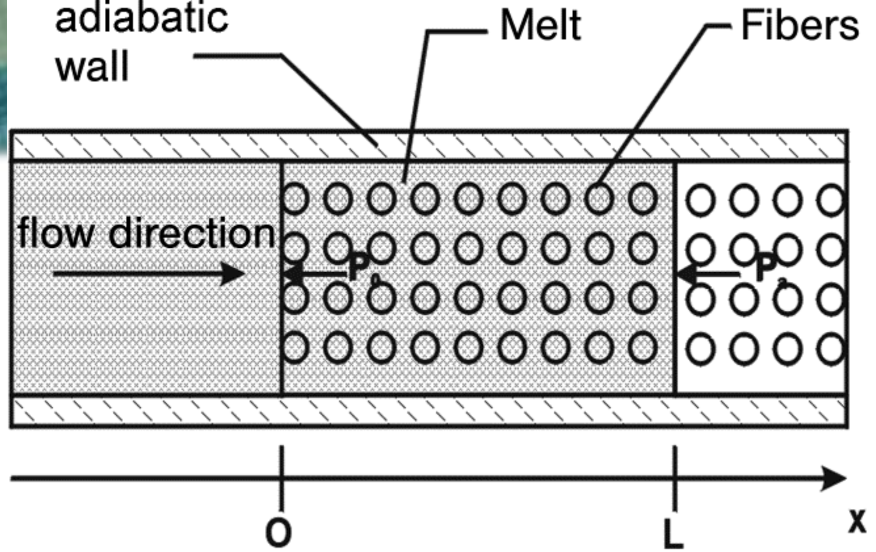
1. *Formation of a contact between the melt and the reinforcement at the surface of a preform*

2. *Infiltration with the melt flow through the preform*

3. *Solidification of the melt*

At the beginning a minimum pressure is usually applied to start inflow of the melt

Spontaneous infiltration is only possible with thin preforms with reactive systems and with long process times



The driving force for the infiltration is the pressure drop in the melt

$$\Delta P = P_o - P_a - \Delta P_Y$$

Where ΔP *is the pressure drop,* P_o *is the pressure in the melt entering the preform,* P_a *is the pressure in the melt at the infiltration front, and* ΔP_Y *is the pressure drop at the infiltration front due to wettability*

The minimum infiltration pressure is defined when $P_o = P_a$

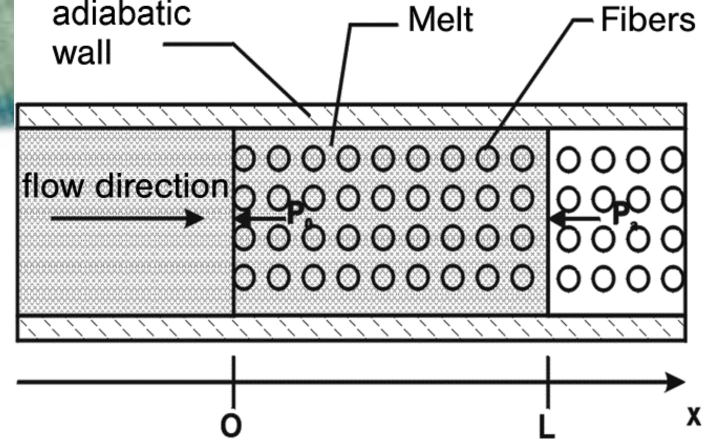
$$\Delta P_{min} = \Delta P_Y = S_f(\gamma_{LS} - \gamma_{SA})$$

Where S_f *is the specific surface of the interphase (area/volume of fiber)*

The effect of induced infiltration by the capillary force is

$$\Delta P_Y = \frac{2 * \gamma_{LA} * \cos\theta}{r}$$

Infiltration of preforms



Pressure-free infiltration is possible depending on the specific surface area, the diameter and the surface energy of the reinforcements

- *For a spherical particle*

$$S_f = \frac{6V_f}{d_f * (1 - V_f)}$$

- *For a long fiber or short fiber preform*

$$S_f = \frac{4V_f}{d_f * (1 - V_f)}$$

- *Specific surface are increases with fiber content in the composite*

Tab. 1.4 Specific surface of Al_2O_3 preforms, after [17] and [48].

Fiber volume content of Al_2O_3 preforms [vol. %]	10	20	24	25
Specific surface: $S_f = 10^6$ fiber surfaces (m^2)/ pore volume (m^3)	1.26	3.41	4.39	4.58

Infiltration of preforms by metal melt

The infiltration pressure also increases with fiber content due to reduced permeability

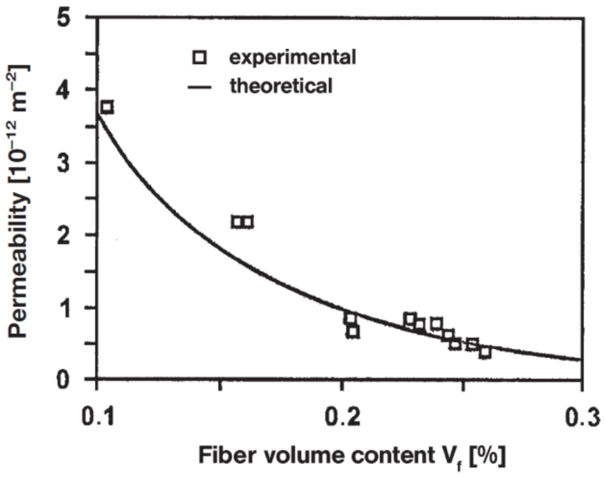
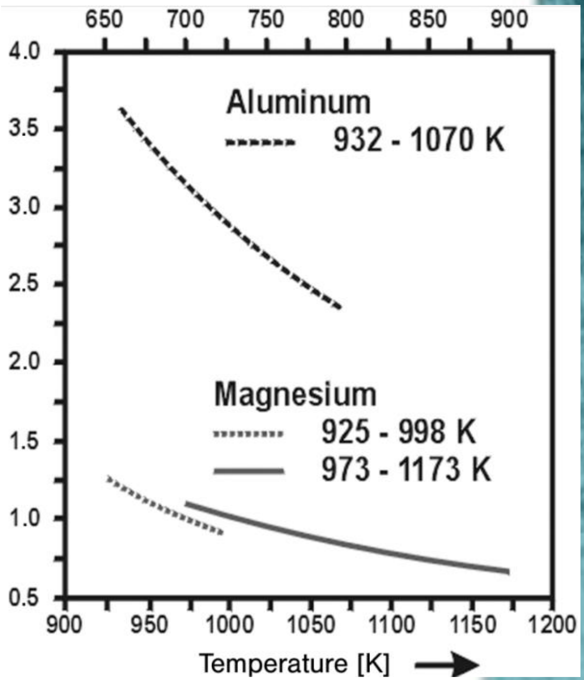
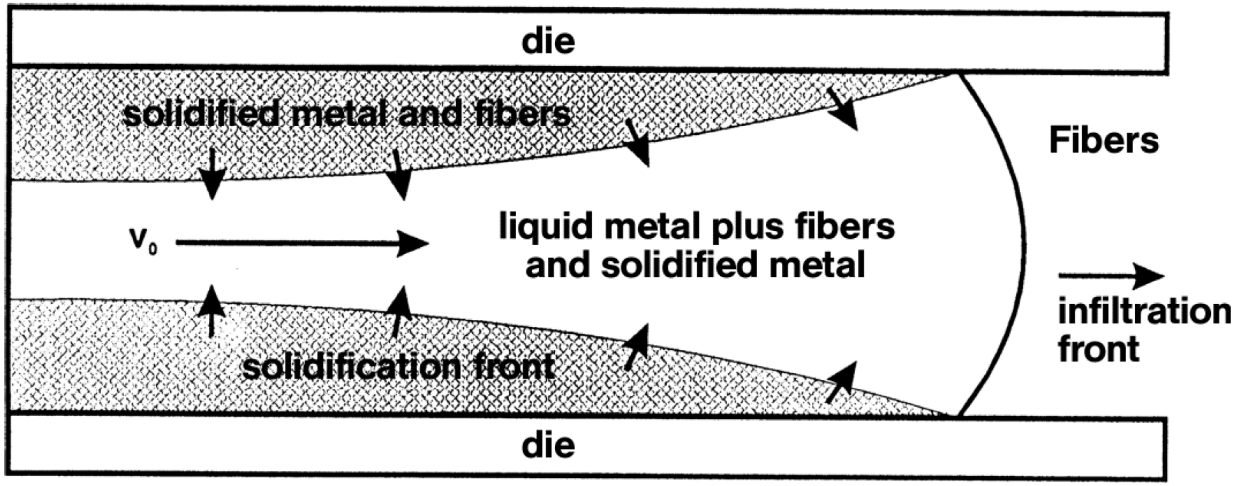


Fig. 1.37 Comparison of permeability of preforms for running water, after Mortensen and calculations of Sangini and Acrivos [48, 49].



Flow of the melt and infiltration become easier at high temperatures due to reduced temperature



In reality partial solidification can occur during infiltration due to the contact of the melt with the die walls and heat dissipation to the reinforcement material

Partial solidification can decrease the permeability and prevent complete infiltration of the preform

Hence increasing the temperature of the melt both decreases viscosity and supplies heat to prevent early solidification

Heating the preform can also help complete infiltration

Tab. 1.5 Comparison of physical data of C fibers and aluminum oxide fibers (Saffil)

Fiber	*Specific heat* ($J\ m^{-3}\ K^{-1}$)	*Coefficient of thermal conductivity* ($W\ m^{-1}\ K^{-1}$)
Carbon P100	1.988×10^{6}	520
Carbon T300	1.124×10^{6}	20.1
Saffil	2.31×10^{6}	0

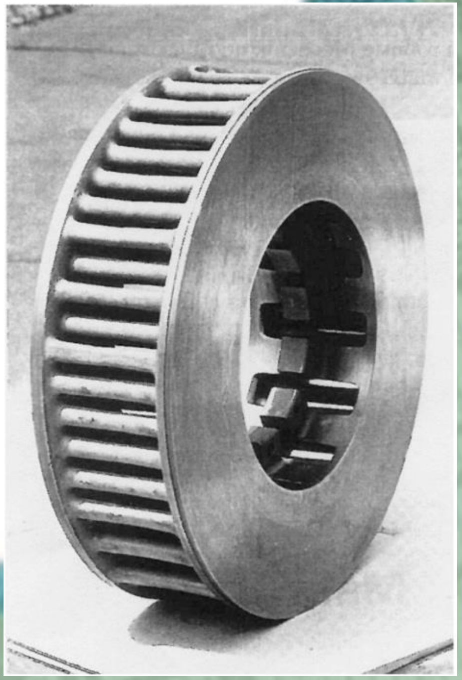
Application areas of MMCs

- *Automotive engineering – engine components (oscillating components: valve train, piston rod, **piston** and piston pin; cover: cylinder head, crankshaft main bearing; engine block: partial strengthened cylinder blocks*

- *Example – Toyota commercial car piston made of partially alumina-silica short fiber-reinforced aluminum*

Application areas of MMCs

- *Powder metallurgically manufactured aluminum alloys and heavy iron in engine components can be effectively replaced by MMCs with improved high temperature properties*
- *Railway or subway cars – transverse control arms,* ***particle-strengthened brake disks***
- *Aerospace industry – reinforcement components, axle tubes, rotors, housing covers, structures for electronic devices*
- *Polymers and PMC components can be replaced with MMC with high specific strength, high stiffness, small thermal expansion coefficient, high thermal resistance and high conductivity*

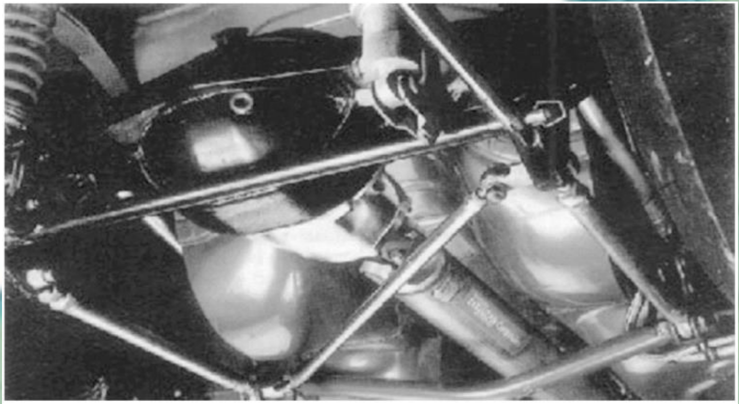


Application	*Required properties*	*Material system*	*Processing technique*
Automotive and heavy goods vehicle			
Bracing systems, piston rods, frames, piston, piston pins, valve spring cap, brake discs, disc brake calliper, brake pads, cardan shaft	High specific strength and stiffness, temperature resistance, low thermal expansion coefficient, wear resistance, thermal conductivity	Al-SiC, Al-Al_2O_3, Mg-SiC, Mg-Al_2O_3, discontinuous reinforcements	Fusion infiltration, extrusion, forging, gravity die casting, die casting, squeeze-casting
Accumulator plate	High stiffness, creep resistance	PbC, Pb-Al_2O_3	Fusion infiltration
Military and civil air travel			
Axle tubes, reinforcements, blade- and gear box casing, fan and compressor blades	High specific strength and stiffness, temperature resistance, impact strength, fatigue resistance	Al-B, Al-SiC, Al-C, Ti-SiC, Al-Al_2O_3, Mg-Al_2O_3, Mg-C continuous and discontinuous reinforcements	Fusion infiltration, hot pressing, diffusion welding and soldering, extrusion, squeeze-casting
Turbine blades	High specific strength and stiffness, temperature resistance, impact strength, fatigue resistance	W super alloys, z. B. Ni_3Al, Ni-Ni_3Nb	Fusion infiltration, aligned solidification near net-shaped components
Aerospace industry			
Frames, reinforcements, aerials, joining elements	High specific strength and stiffness, temperature resistance, low thermal expansion coefficient, thermal conductivity	Al-SiC, Al-B, Mg-C, Al-C, Al-Al_2O_3, continuous and discontinuous reinforcements	Fusion infiltration, extrusion, diffusion welding and joining (spacial structures)
Energy techniques (electrical components and conducting materials)			
Carbon brushes	High electrical and thermal conductivity, wear resistance	Cu-C	Fusion infiltration, powder metallurgy
Electrical contacts	High electrical conductivity, temperature and corrosion resistance, burn-up resistance	Cu-C, Ag-Al_2O_3, Ag-C,Ag-SnO_2, Ag-Ni	Fusion infiltration, powder metallurgy, extrusion, pressing
Super conductor	Superconducting, mechanical strength, ductility	Cu-Nb, Cu-Nb_3Sn, Cu-YBaCO	Extrusion, powder metallurgy, coating technologies
Other applications			
Spot welding electrodes	Burn-up resistance	Cu-W	Powder metallurgy, infiltration
Bearings	Load carrying capacity, wear resistance	Pb-C, Brass-Teflon	Powder metallurgy, infiltration

Examples

Drive shaft for light load motor vehicles (substitution of steels)

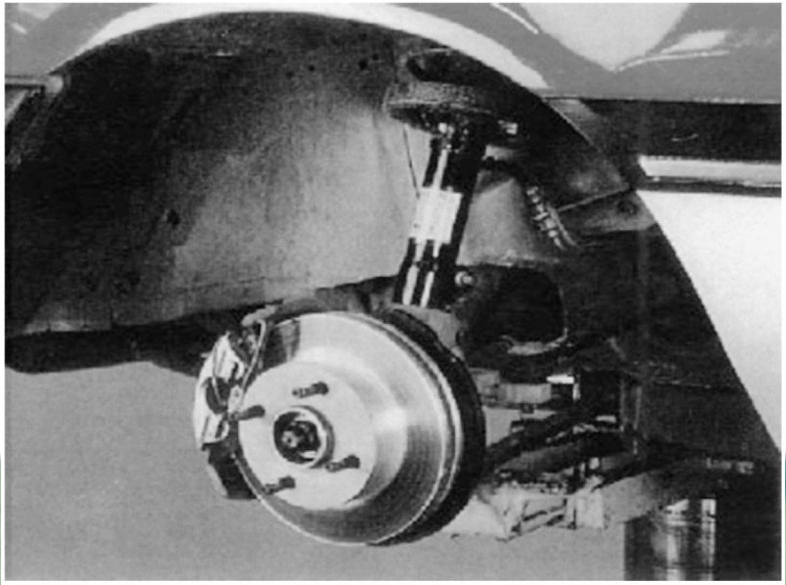
- *AlMg1SiCu + 20 vol% Al2O3 particles processed with die casting and extrusion*
- *High dynamic stability*
- *High stiffness (95 GPa)*
- *High fatigue strength (120 MPa at n=50000000 and room temperature)*
- *Sufficient toughness (21.5 MPa.m1/2)*
- *Low density (2.95 g/cc)*



Examples

Vented passenger car brake disk (substitution of cast iron)

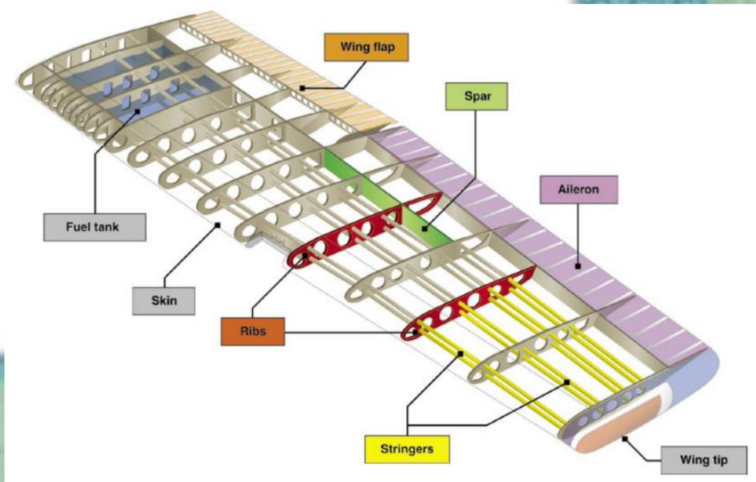
- *G-AlSi12Mg + 20 vol% SiC particles processed with sand or gravity die casting*
- *High wear resistance*
- *Low heat conductivity (higher than cast iron)*



Examples

Longitudinal bracing beam (Stringer) for planes (substitution of PMC)

- *AlCu4Mg2Zr + 15 vol% SiC particles processed by die casting followed by extrusion and forging*
- *High dynamic stability (E=100 GPa)*
- *High strength (yield= 413 MPa, max= 540 MPa)*
- *High fatigue strength (240 MPa for n= 50000000 at room temperature)*
- *Sufficient toughness (19.9 MPa.m1/2)*
- *Low density (2.8 g/cc)*



Examples

- *Disk brake calliper for train cars (substitution of cast iron)*
- *Aluminium alloy with Nextel ceramic fiber 610*
- *55% lighter compared to cast iron*