# Composite Materials

Metal matrix composites

# Introduction

- The properties that make MMCs attractive are high strength and stiffness, good wear resistance, high service temperature, tailorable coefficient of thermal expansion and thermal conductivity
- MMCs are brittle
- MMCs have high material and production costs
- Ceramic and polymer matrix composites are manufactured to their final shape at the same time as the microstructure of the material is formed
- MMCs can be produced by both this way or as traditionally done with metals (billets or sheets are later machined to a final shape)
- In comparison to PMCs, their shear, compressive and high T strength are better. Also their physical stability is higher

# Introduction

Due to the low volume of production, MMC processing techniques are not as well established as PMC processes

- One of the two groups of commercial MMCs are very high performance composites reinforced with expensive continuous fibers and requiring expensive processing methods

Their applications are currently limited to advanced military and space applications because they are produced in small volumes which increase the manufacturing costs

- The other consists of relatively low-cost and low performance composites reinforced with relatively inexpensive particulate or fibers. This group has small benefit in properties over alternative materials

# Introduction

Metal matrix composites consist of lightweight metal alloys as matrices of aluminum, magnesium, titanium

The reinforcement of these light metals opens up the possibility of application of these materials in areas where weight reduction is important

The main objectives for light metal composite materials are

- Increase in yield strength and tensile strength at room and higher temperatures while maintaining ductility
- Increase in creep resistance at higher temperatures
- Increase in fatigue strength especially at high temperatures
- Improvement of thermal shock resistance
- Improvement of corrosion resistance
- Increase in Young’s modulus
- Reduction of thermal elongation

# Reinforcements

Light alloy metals are reinforced with ceramic particulate, whiskers or fibers because they have low density, a low thermal expansion coefficient, chemical compatibility with metals, thermal stability, high Young's modulus, high compression strength

The use of metallic fibers usually fails due to their high density and the affinity to reaction with the matrix

- The most common types of particulate are alumina, boron carbide, silicon carbide, titanium carbide and tungsten carbide.
- The most common type of whisker is silicon carbide, and whiskers of alumina and silicon nitride are also used
- Boron carbide and silicon carbide particles are widely used abrasives that produce good wear resistance and high specific stiffness.
- Titanium carbide offers a high melting point and chemical inertness
- Tungsten carbide has high strength and hardness at high temperature

# Reinforcements

| *Reinforcement* | *Saffil ($Al_2O_3$)* | *SiC particle* | *$Al_2O_3$ particle* |
|---|---|---|---|
| crystal structure | $\delta$-$Al_2O_3$ | hexagonal | hexagonal |
| density ($g\ cm^{-3}$) | 3.3 | 3.2 | 3.9 |
| average diameter (μm) | 3.0 | variable | variable |
| length (μm) | ca. 150 | – | – |
| Mohs hardness | 7.0 | 9.7 | 9.0 |
| strength (MPa) | 2000 | – | – |
| Young's Modulus (GPa) | 300 | 200–300 | 380 |

# Reinforcements

Continuous reinforcements are the most common type.

Ceramic fibers and carbon fibers are utilized in metal matrix composites as reinforcements

Wire reinforcement is a less common type of continuous reinforcement.

They are made of such metals as titanium, tungsten, molybdenum, beryllium and stainless steel

Tungsten wire provides good high temperature creep resistance especially for components in aerospace vehicles

| *MMC type* | *Properties Strength* | *Young's modulus* | *High temperature properties* | *Wear* | *Expansion coefficient* | *Costs* |
|---|---|---|---|---|---|---|
| mineral wool: MMC | * | * | ** | ** | * | medium |
| discontinuous reinforced MMC | ** | ** | * | *** | ** | low |
| long fiber reinforced MMC: C fibers | ** | ** | ** | * | *** | high |
| other fibers | *** | *** | *** | * | ** | high |

# Reinforcements

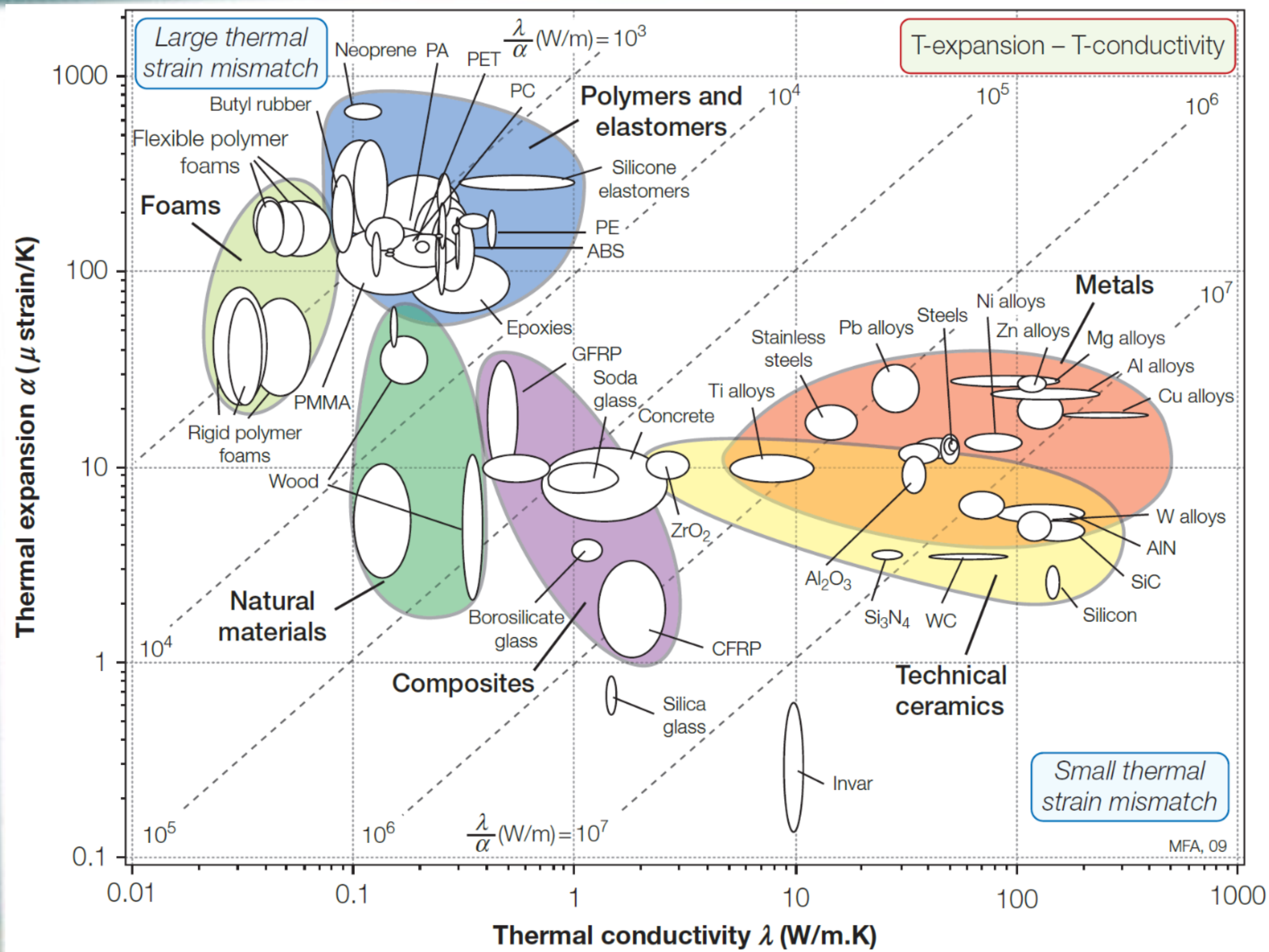
Ceramic reinforced metal matrix composites have lower thermal expansion coefficient than metals

Their thermal and electrical conductivities are lower than metals

In addition MMCs have very high thermal deformation resistance which is especially important for spacecrafts

- TDR = thermal conductivity / thermal expansion coefficient
- Example – Magnesium has very low TDR but adding C fibers increase it up to 6000%

There is a volume percentage limitation to reinforcements added to metal matrices as ductility decreases and processing becomes difficult



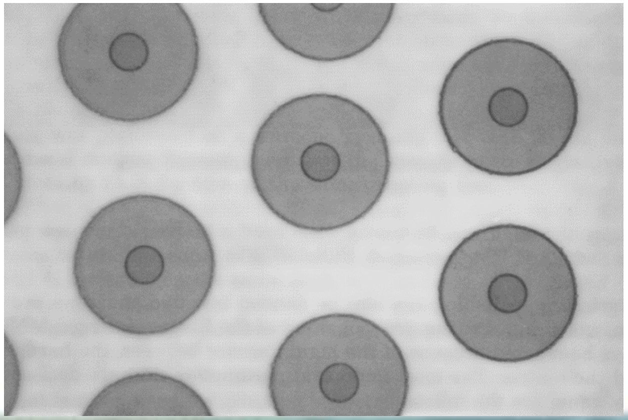
T-expansion – T-conductivity
Large thermal strain mismatch
Small thermal strain mismatch
$\frac{\lambda}{\alpha}$(W/m) = $10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$\frac{\lambda}{\alpha}$(W/m) = $10^7$
Polymers and elastomers
Foams
Natural materials
Composites
Metals
Technical ceramics
Neoprene
PA
PET
PC
Butyl rubber
Flexible polymer foams
Silicone elastomers
PE
ABS
Epoxies
PMMA
Rigid polymer foams
Wood
GFRP
Soda glass
Concrete
Borosilicate glass
CFRP
Silica glass
Invar
$ZrO_2$
Stainless steels
Ti alloys
Pb alloys
Steels
Ni alloys
Zn alloys
Mg alloys
Al alloys
Cu alloys
W alloys
AlN
SiC
Silicon
$Al_2O_3$
$Si_3N_4$
WC
MFA, 09
Thermal expansion $\alpha$ ($\mu$ strain/K)
Thermal conductivity $\lambda$ (W/m.K)
0.1
1
10
100
1000
0.01
0.1
1
10
100
1000

# Structure of MMCs

The structure of the composite material is determined by the type and form of the reinforcement components, whose distribution and orientation are affected by the manufacturing process.

- For composites with long fibers, microstructure show extreme differences with different fibers

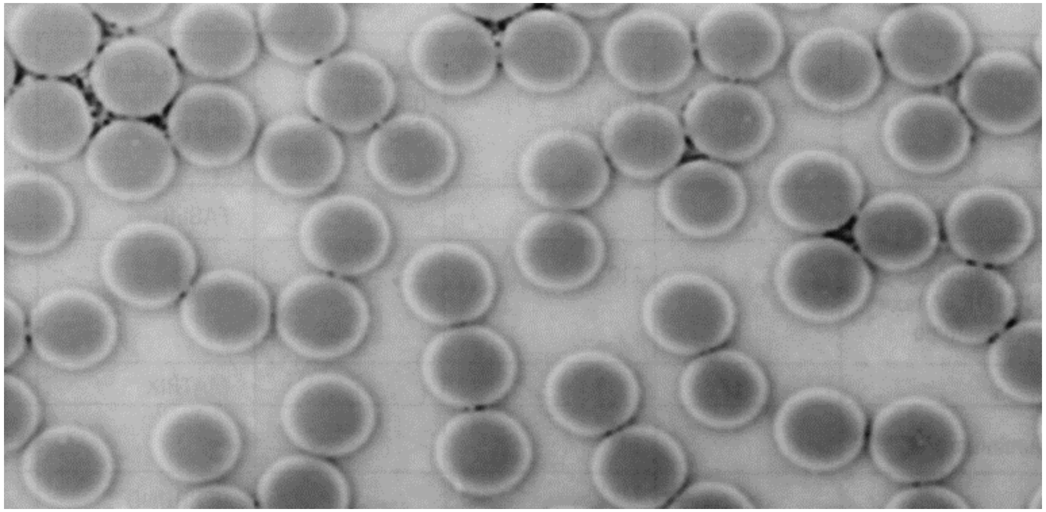
The ideal structure is seen below for a SiC monofilament reinforced titanium



# Structure of MMCs

Fiber-fiber contacts, nonreinforced areas, pores are defects in composite structure that are most often seen when fiber textile preforms are used

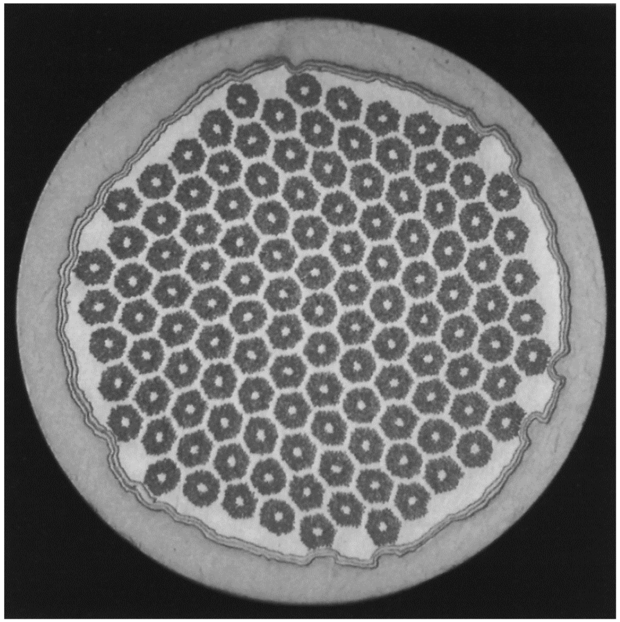
- Endless alumina fiber reinforced aluminum



# Structure of MMCs

Long fiber composites can be made exceptionally uniform with the right production process

- Composite superconductor CuSn with ceramic fibers in a shell



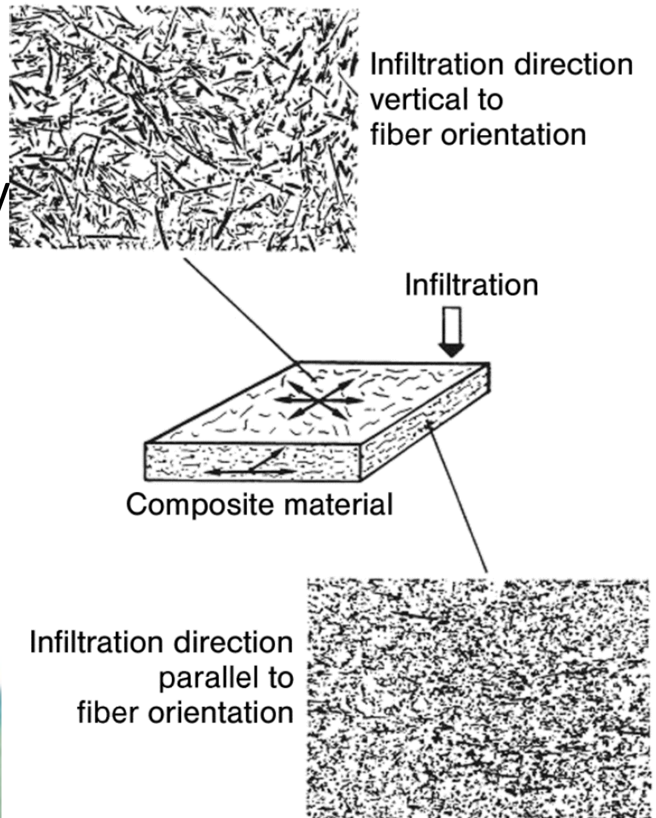
Tab. 1.6 Selected properties of typical long fiber reinforced light metal composites.

| Material | | Fiber content (%) | Density (g cm$^{-3}$) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|---|
| System | Orientation | | | | |
| Monofilaments | | | | | |
| B/Al | 0° | 50 | 2.65 | 1500 | 210 |
| B/Al | 90° | 50 | 2.65 | 140 | 150 |
| SiC/TiAl6V4 | 0° | 35 | 3.86 | 1750 | 300 |
| SiC/TiAl6V4 | 90° | 35 | 3.86 | 410 | |
| Multifilaments | | | | | |
| SiC/Al | 0° | 50 | 2.84 | 259 | 310 |
| SiC/Al | 90° | 50 | 2.84 | 105 | |
| $Al_2O_3$/Al–Li | 0° | 60 | 3.45 | 690 | 262 |
| $Al_2O_3$/Al–Li | 90° | 60 | 3.45 | 172–207 | 152 |
| C/Mg-Leg | 0° | 38 | 1.8 | 510 | |
| C/Al | 0° | 30 | 2.45 | 690 | 160 |
| SiC/Al | Al + 55–70% SiC | | 2.94 | | 226 |
| MCX-736™ | Al + 55–70% SiC | | 2.96 | | 225 |

# Structure of MMCs

With short-fiber reinforced composite materials a planar-isotropic distribution of the short fibers develops due to the fiber molded production

Fibers sediment to the bottom of the mold to create layers. The infiltration direction is generally perpendicular to these layers



# Structure of MMCs

The strength of short-fiber reinforced metal composites increase with fiber content and type significantly

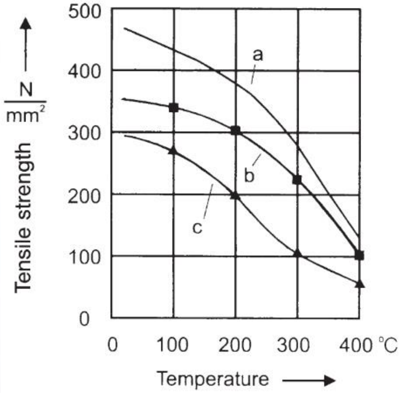



**Fig. 1.54** Comparison of temperature dependence of the tensile strength of nonreinforced and reinforced piston alloy AlSi12CuMg (KS 1275) [13]: (a) KS 1275 with 20 vol.% SiC whisker; (b) KS 1275 with 20 vol.% $Al_2O_3$ fibers; (c) KS 1275 nonreinforced.

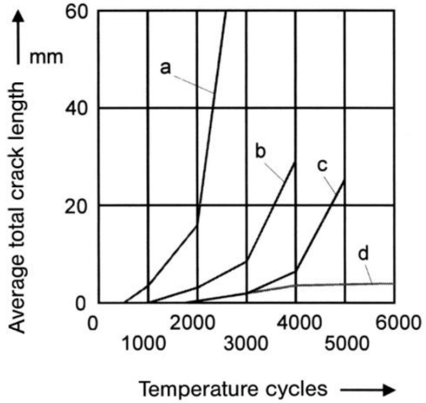



**Fig. 1.56** Temperature shock resistance of the fiber reinforced piston alloy AlSi12CuMgNi (KS1275) for different fiber contents for a temperature of 350 °C [13]: (a) Nonreinforced, (b)12 vol.% $Al_2O_3$ short fibers, (c)17.5 vol.% $Al_2O_3$ short fibers, (c) 20 vol.% $Al_2O_3$ short fibers.

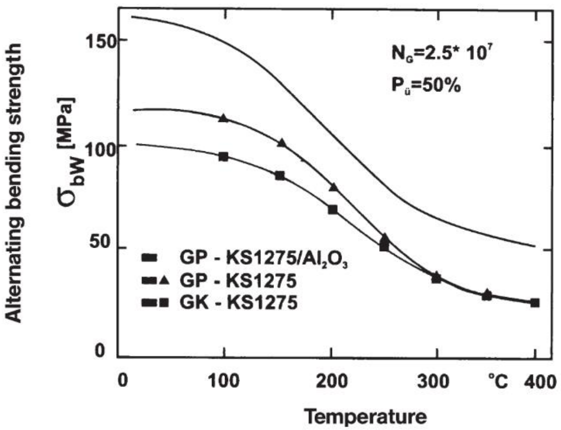


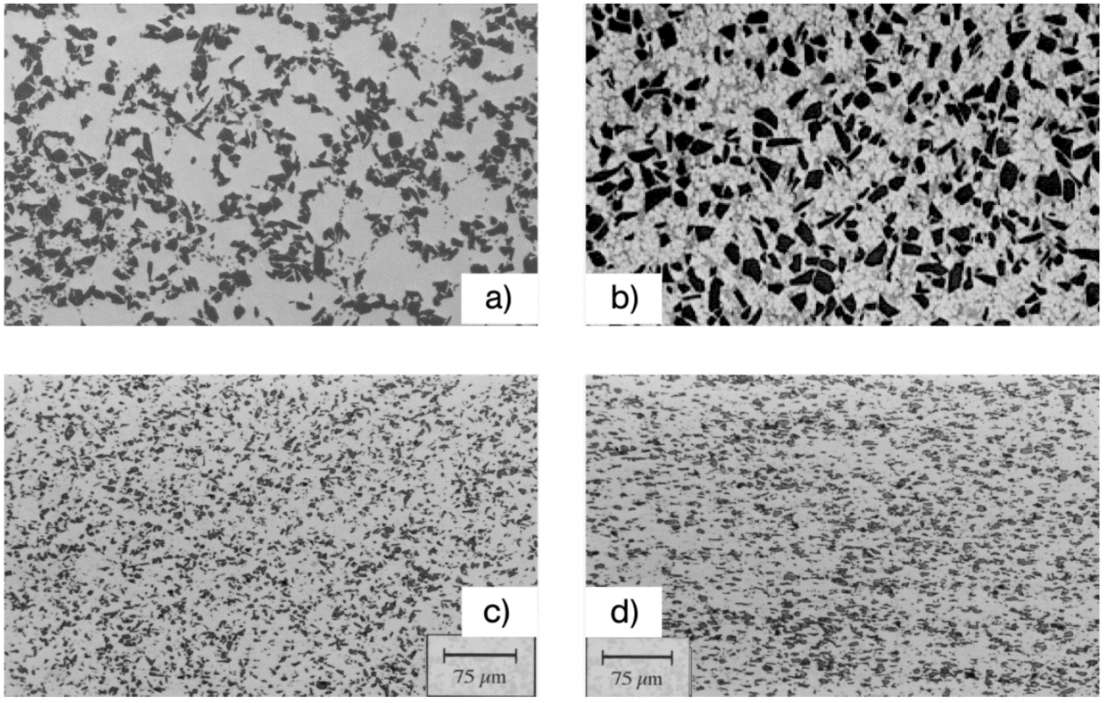

**Fig. 1.55** Change in the alternating bending strength of nonreinforced and reinforced piston alloy (20 vol.% $Al_2O_3$ fibers) AlSi12CuMgNi (KS1275), with increasing temperature (GK=mold casting, GP=die casting) [14].

Some of these composites are ideal for applications such as pistons or cylinder surfaces in engines

# Structure of MMCs

The microstructure of particle reinforced metal composites depends on the processing methods

- Gravity die cast composites show nonreinforced areas due to the solidification conditions (a)
- Pressure die cast composites have better distribution of particles (b)
- Even better results are reached after the extrusion of the powder mixture (c)
- The particles are extremely homogeneously distributed in powder metallurgically manufactured and extruded powder mixtures (d)




SiC reinforced Al

# Mechanical properties

In general MMCs have higher mechanical properties than their metal counterparts and the particle addition to light metals results in increase in the hardness, modulus, yield strength, tensile strength and the wear resistance

The stiffness and strengths of particulate reinforced aluminum MMCs are significantly better (>1.5x) than those of the aluminum matrix

In comparison with advanced polymer matrix composites, particulate MMCs which are isotropic, have lower strength than the strength parallel to the direction of continuous fiber reinforced PMCs and much higher strength than the transverse strength of PMCs

# Mechanical properties

The stiffness of particulate reinforced MMCs are about the same as that of PMCs

**Table 4.2.—Structural Properties of Representative MMCs, Compared to Other Materials**

| Property | Matrix(l)* metal[a] | Particulate(2)* MMC[a] | Fiber(3)* MMC[a] | PMC[b] | Ceramic[b] |
|---|---|---|---|---|---|
| Strength (M Pa) (axial) | -290 | 290-480 | 620-1,240 | 820-1,680 | 140-3,900 |
| Stiffness (G Pa) (axial) | -70 | 80-140 | 130-450 | 61-224 | 97-400 |
| Specific strength (axial) | -100 | 100-170 | 250-390 | 630-670 | 51-670 |
| Specific gravity | 2.5-2.8 | -2.8 | 2.5-3.2 | 1.3-2.5 | 2.7-5.8 |
| Transverse strength (MPa) | -290 | 290-480 | 30-170 | 11-56 | 140-3,900 |
| Transverse stiffness (GPa) | Same as axial | Same as axial | 34-173 | 3-12 | Same as axial |
| Maximum use temperature (“C) | 180 | 300 | 300 | 260 | 1,200-1,600 |
| Plane strain fracture toughness (MPa-m[½]) | 18-35 | 12-35 | — | — | 3-9 |

PMC is used to denote a range of materials including graphite/epoxy, graphite/polylmlde, boron/polyimide, and S-glass/epoxy
Ceramic is used to denote a range of materials including zirconia, silicon carbide, and silicon nitride
“NOTE: (1) 6061 aluminum
(2) 6061 aluminum reinforced with 0-400/0 volume fractions of SiC particulate
(3) 6061 aluminum reinforced with 50°/0 volume fractions of fibers of graphite, boron. silicon carbide, or alumina

# Mechanical properties

Fiber reinforced MMCs can be highly anisotropic, having different strengths and stiffnesses in different directions

Their strength and stiffness are much higher than in the unreinforced metal (6x)

However in the transverse direction there is not much improvement over the matrix material

In comparison to continuous fiber reinforced PMCs, transverse strengths and stiffnesses are much higher

**Table 4-3.—Strength and Stiffness of Some Fiber. Reinforced MMCs (Fiber v/o = 50%)**

| Material<br>Matrix material | Tensile strength (axial) MPa | Tensile strength (transverse) MPa | Stiffness (axial) GPa | Stiffness (transverse) GPa |
|---|---|---|---|---|
| Aluminum 6061-T6 ...., | 290 | 290 | 70 | 70 |
| Titanium Ti-6Al-4V | 1170 | 1170 | 114 | 114 |
| *Composite* | | | | |
| Graphite[a]/aluminum . . . | 690 | 30 | 450 | 34 |
| Boron/aluminum. . . . . | 1240 | 140 | 205 | 140 |
| Silicon carbide[b]/ aluminum . . . . . . | 1240 | 100 | 205 | 140 |
| Silicon carbide[c]/ aluminum . . . . . . . . . | 1040 | 70 | 130 | 99 |
| Alumina[d]/aluminum . . . . . | 620 | 170 | 205 | 140 |
| Silicon carbide[e]/ titanium . . . . . . . . . . . . . | 1720 | 340 | 260 | 173 |
| Graphite[a]/copper . . . . . . . . | 512 | 31 | 464 | 49 |

Properly Improvements of MMCs over unreinforced metals can be significant For example, the axial stiffness of graphite fiber-reinforced aluminum is roughly 6 times greater than that of the unreinforced aluminum The axial tensile strength of silicon carbide fiber-reinforced aluminum is about 4 times greater than that of the unreinforced aluminum

aP-120

[b]AVCO monofilament

[c]"Nicalon"

[d]Fibe,"FP"

[e]AVCO monofilament

# Mechanical properties

In short, particulate MMCs have slightly better specific strength and specific stiffness than the matrix metal while fiber reinforced MMCs have much better specific strength and stiffness than the matrix metal

Hence fiber reinforced MMCs are suitable for high strength, low weight applications like aircraft structures.

However in comparison to PMCs they have a higher density and lower specific strength and specific stiffness in the axial direction

Transverse specific strength and specific stiffness of MMCs are better than those of PMCs

# Mechanical properties

One of the major advantages of MMCs is their high wear resistance compared to monolithic metals and PMCs

This is majorly due to the presence of hard ceramic reinforcements

Example – The abrasive wear of 2024 aluminum – 20% silicon carbide whisker composite has 6X less wear under load than the metal matrix

Similarly an alumina-silica fiber reinforced aluminum piston used in Toyota automobiles gave 85% improvement in wear resistance over cast iron pistol with nickel component

# Mechanical properties

The fracture toughness of MMCs vary between 65 and 100% of the fracture toughness of the monolithic metal

Generally higher strength and stiffness in the reinforced composite result in a decrease the fracture toughness

This brittleness can make processing and joining of highly reinforced MMCs

- Example – aluminum reinforced with silicon carbide particulate

**Table 4-4.—Properties of 6061 Aluminum Reinforced With Silicon Carbide Particulate**

| Reinforcement | Stiffness (G Pa) | Tensile strength (M Pa) | Tensile strain |
|---|---|---|---|
| 0% | 10 | **290** | **16.0%** |
| **10** | **83** | | 7.0 |
| 15 | 86 | 3&I | 6.5 |
| 20 | 90 | 430 | 6.0 |
| 25 | 103 | — | 3.5 |
| 30 | 117 | 470 | 2.0 |
| 35 | 124 | — | 1.0 |
| **40** | **140** | **480** | **0.6** |

**Note the sharp rise** in stiffness in the 400/0 composite (140 GPa) compared to the unreinforced aluminum (10 GPa). Ultimate tensile strength nearly doubles and tensile strain decreases nearly a full order of magnitude.

# Thermal properties

Service temperature is an important design criterion as materials lose their elasticity at high temperatures

MMCs provide improved elevated temperature strength and modulus over both PMCs and metals

- Reinforcements make it possible to extend the useful temperature range of low density metals such as aluminum which have limited high temperature capability (180 C)
- MMCs typically have higher strength and stiffness than PMCs between 200-300 C

At higher service temperatures no other structural material can replace ceramics

# Thermal properties

At high temperatures fiber reinforced MMCs experience matrix/reinforcement interface reactions

Coatings are therefore essential in many MMCs to form an interphase between the matrix and the fibers

- Example – Boron fiber in aluminum, coated with boron carbide

One other shortcoming of fiber reinforced MMCs is that their transverse high temperature strength is equal to that of the matrix metal since mechanical properties in the transverse direction are dominated by the matrix

- Example – The axial tensile strength of boron fiber reinforced aluminum is about 1100 MPa and the transverse strength is 80 MPa (70 MPa for monolithic 6061 aluminum)

MMCs are generally good heat conductors and have low coefficient of thermal expansion

- Example – silicon carbide particulate reinforced aluminum

# Chemical properties

- The corrosion resistance of MMCs are similar to PMCs but inferior to CMCs
- They resist water damage due moisture absorption which is a major shortcoming for PMCs at high temperature usage
- On the other hand graphite fibers undergo corrosion reaction with aluminum in the presence of air and moisture
- In addition acids and other corrosive chemicals affect metals and MMCs more

# Processing

MMC production processes can be divided into primary and secondary processing methods

1. Used to form the material: combining and consolidation operations
2. Used to machine the component: shaping and joining operations

Net-shape methods are very important manufacturing processes as the machining of MMCs is very difficult and costly due to the abrasiveness

Also it is necessary to reduce the amount of scrap left from the machining process

# Processing

**Table 4-5.—MMC Manufacturing Methods**

| | Combines | Consolidates | Shapes | Joins |
|---|---|---|---|---|
| ***Primary methods:*** | | | | |
| Casting<br>Squeeze casting,<br>compocasting,<br>gravity casting,<br>low-pressure casting | x | x | x | |
| Diffusion bonding | | x | x | x |
| Liquid infiltration<br>Gravity,<br>inert gas pressure,<br>vacuum infiltration | x | x | | |
| Deposition<br>Chemical coating,<br>plasma spraying,<br>chemical vapor deposition,<br>physical vapor deposition,<br>electrochemical plating | X | X | | |
| Powder processing<br>Hot pressing,<br>ball mill mixing,<br>vacuum pressing,<br>extrusion, rolling | X | X | X | |
| ***Secondary methods:*** | | | | |
| Shaping<br>Forging, extruding, rolling,<br>bending, shearing, spinning,<br>machining | | X | X | |
| Machining<br>Turning, boring,<br>drilling, milling,<br>sawing, grinding, routing,<br>electrical discharge machining<br>chemical milling,<br>electrochemical milling | | | x | |
| Forming<br>Press brake,<br>superplastic,<br>creep forming | | x | x | x |
| Bonding<br>Adhesive, diffusion | | | | X |
| Fastening | | | | X |
| Soldering, brazing, welding | | | | X |

# Processing

Different manufacturing processes are suitable for continuous and particulate reinforced MMCs

- For MMCs with continuous reinforcement

Primary processes include liquid metal infiltration, modified casting processes, deposition methods like plasma spraying, hot pressing, diffusion bonding

- Example – The Toyota diesel engine piston is produced using modified casting process

Secondary processes for MMCs reinforced with ceramic fibers which are hard and abrasive, require diamond tools that do not wear out. All basic mechanical methods that are applicable to metals like drilling, sawing, milling, turning, riveting, bolting are effective with MMCs.

Adhesive bonding processes like soldering, brazing, welding and diffusion bonding are also applicable

# Processing

- For MMCs with particulate reinforcement

Primary processes include powder processing techniques, liquid metal infiltration and casting techniques

Secondary processes: Most of the conventional metal working processes can be used with minor modifications (forging, extruding, rolling, bending, shearing and machining). All conventional machining methods also work with particulate reinforced MMCs using diamond tools

# Processing

**Table 4-6.—Selected MMC Processing Techniques and Their Characteristics**

| Techniques | Characteristics |
| --- | --- |
| ***For fiber-reinforced MMCs:*** | |
| Liquid metal infiltration (low pressure) | near-net-shape parts<br>economical<br>high porosity<br>oxidation of matrix and fiber<br>not reliable as yet |
| Liquid metal infiltration (intert gas pressure, vacuum) | less porosity and oxidation than low pressure techniques |
| Low pressure casting | near-net-shape parts<br>low cost<br>expensive preforms required<br>three-dimensional preforms are difficult to make |
| Squeeze casting | good fiber wetting<br>lower porosity<br>expensive molds needed<br>large capacity presses needed |
| Plasma spraying | potential for lower processing costs |
| Diffusion bonding | lower temperatures than hot pressing<br>reduces fiber/matrix interactions<br>not capable of net-shape parts except simple shapes<br>slow, expensive<br>fiber damage can occur |
| Hot Pressing | heats matrix above melt temperature, which can degrade reinforcement |
| ***For particulate-reinforced MMCs:*** | |
| Powder metallurgy | high volume fractions of particulate are possible (better properties)<br>powders are expensive<br>not for near-net-shape parts |
| Liquid metal infiltration | net-shape parts<br>can use ingots rather than powders<br>lower volume fraction of particulate (means lower mechanical properties) |
| Squeeze casting | may offer cost advantage; however molds and presses may be expensive |

# Future

In order to increase the applicability of MMCs, three areas need to be researched:

1. Cheaper processes: Manufacturing processes such as plasma spraying, powder metallurgy processes, modified casting techniques, liquid metal infiltration and diffusion bonding should be optimized
2. Cheaper materials: Development of lower cost fiber reinforcements is a major need
3. Coatings: Coatings enable a reinforcement type to be used with many matrix types. They can prevent deleterious chemical reactions at high temperatures at the interface and optimize the interfacial fiber/matrix bond

Other areas of research that promise improvement in MMC properties are environmental behavior, fracture behavior, nondestructive evaluation methods, machining processes