Aluminium and Magnesium Based Metal Matrix Composites

Kompoziti na osnovi Al in Mg

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Prejem rokopisa - received: 1996-10-01; sprejem za objavo - accepted for publication: 1996-11-04

In motor-cars metal matrix composites (MMC's) are employed in braking systems and engine components. Other applications for these materials have been developed in energy and in information applications. The potentional of composite materials is very great because the properties can be tailored according to the application. There are many possible material combinations and processing techniques which can be employed. For structural applications standard light metal are often strengthened by ceramic fibres or particles. The performance and potential of composites will be discussed using examples of reinforced aluminium and magnesium alloys.

Key words: Al and Mg based MMC's, Al and Mg alloys, SiC and Al_2O_3 as reinforcement, properties, applications, processing techniques

Kompoziti s kovinsko osnovo, ojačani s keramičnimi delci ali vlakni se danes že uporabljajo kot deli zavornega sistema in motorjev z notranjim izgorevanjem. Razvite so tudi posebne vrste teh materialov, ki so uporabni na področju energetike in informatike. Uporabnost kompozitnih materialov je vsestranska, ker lahko njihove lastnosti prilagajamo potrebam uporabe. Možne so številne kombinacije materialov (kovinska osnova / keramična ojačitev) in postopkov njihove izdelave. Kompoziti, ki se uporabljajo kot konstrukcijski materiali so najpogosteje sestavljeni iz lahke kovinske osnove in keramičnih delcev ali vlaken. Prispevek obravnava predvsem dosežene lastnosti in možnosti uporabe kompozitov z osnovo iz Al ali Mg zlitin, ki so diskontinuirno ojačane z SiC ali Al_2O_3 delci oziroma kratkimi vlakni.

Ključne besede: kompoziti s kovinsko osnovo, Al in Mg zlitine, SiC in Al_2O_3 kot ojačitvena faza, lastnosti, uporaba, postopki izdelave

1 Introduction

The strenuous efforts to develop metal matrix composites with light metal matrices in the eighties have paid off with successful applications in automobile and transport systems. Worthy of mention are partially reinforced pistons, hybrid reinforced engine blocks for cars or trucks as well as particle reinforced brake discs for light lorries, motocycles, cars or rail vehicles. Further fields of applications are military aircraft and space craft. The innovative materials are interesting possibilities in the development of modern materials because the properties of MMC's can be tailored for a particular application and hence MMC's can fulfill all requirements of the designer. Such materials become important when the property profile cannot be achieved by the conventional light metal alloys. The specific strength as outstanding advantage of light metal MMC's is however under pressure from competing technologies such as powder metallurgy of polymer technology. The advantages of composites are only realised if a resonable cost performance ratio is achievable on production of the component. In this respect it is important for economic and ecological reasons to recycle scrap components, production waste, etc.

The aims in the reinforcement of metal matrix functional or structural materials are on the one hand the optimisation of some critical properties at the same time as maintaining other properties and on the other hand a complete change in the property profile of a class of materials. The reinforcement of light metals opens, for example, an extension of the application potential where weight reduction of components is very desirable at the same time as optimisation of component properties. The development aims of light metal matrix composites thus can be sumarised as follows:

- increase in yield strength, ultimate tensile strength and fatigue strength at room temperature whilst maintaining minimum values of ductility or toughness,
- increase in hot strength, fatigue strength and creep resistance at elevated temperatures compared to conventional materials,
- reduction in the coefficient of thermal expansion of light metal alloys to values comparable with steels,
- improvement in the stability of light metals to temperature changes,
- improvement in damping behaviour,
- improvement in the wear resistance through addition of hard materials,
- improvement in weight specific properties (strength and E-modulus).

Discontinuous particle, fibre or whisker reinforced light alloys are most likely to fulfill design criteria because the components are relatively cheap and production of components in large numbers is possible. Further advantages are the relatively high isotropy of properties compared to the long continuous fibre reinforced light metals and the possibility of further forming by forging and machining.

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2 Combination of materials for light alloy composites

The obvious candidates for light metal matrices for composite materials are the easily workable, conventional alloys. Particulary when powder metallurgical (P/M) production techniques are employed it is possible to consider special alloys with specific compositions. P/M technology allows the use of alloys with super satorated or metastable phases. The alloys are free from segregation problems as often observed after conventional solidification.

Examples of extensively investigated matrix alloys are[1-8]:

Conventional Casting Alloys:

Al alloys:	AlSi12CuMgNi
	AlSi9Mg
	AlSi7 (A 356)
Mg alloys:	MgAl9Zn1 (AZ91)
	MgAl2RE2Zr1 (MSR, QE 22)

Conventional wrought alloys:

Al alloys:	AlMgSiCu (6061)
	AlCuSiMn (2014)
	AlZnMgCu1 5 (7075)
Mg alloys:	MgAl3Zn (AZ 31)
	MgZn6Zr (ZK 60)
	MgZn6Cu3 (ZC 63)

Special alloys:

Al alloys:	Al-Cu-Mg-Li (8090)
Mg alloys:	Mg99,5 + RE, Ca, Zr, Ba, Br, Sb or Sn (1-2.4%)

A wide variety of reinforcement materials are available with a wider range of properties. The choice depends on the method chosen for production and on the matrix alloy system. In general the requirements are:

- low density,
- mechanical compatability (a thermal coefficient of expansion which matches the matrix),
- chemical compatability,
- thermal stability,
- high elastic modulus, high compressive and tensile strength,
- good workability,
- economicy.

These demands can be fulfilled virtually only by inorganic reinforcing materials. Often only ceramic particles or fibres or carbon fibres are used to reinforce metals. The use of metallic fibres results in prohibitive increases in density. Which component is chosen depends on the matrix material and the property profile of the particular application. Information of available particles, short fibres, whiskers and continuous fibres for reinforcement of metals is collected in **Table 1** and in references[9,10]. The preparation, working and means of applications of the various reinforcements depends on the method chosen to produce the composite (see[1]). A combinated application of two and more reinforcement material is possible (hybrid technique)[1,9].

3 Production of light metal composites

There are several possible methods of producing semi finished material and components in light metal composites, which depend primarily on the component geometry and the material systems (matrix / reinforcement). The process must be divided into preparation of suitable starting material, production of the semi finished material or component and finishing operations. For economic reasons near net shape production should be attempted to minimise mechanical finishing operations. In general the following production techniques are available:

- *Casting techniques*
  - infiltration of short fibres, particle or hybrid preforms by squeeze casting, vacuum infiltration or pressure infiltration[1,4,7,8],

Table 1: Examples of particles, whisker, continuous and discontinuous fibres used a reinforcements in metal alloys (*CTE = coefficient of thermal expansion, [1)]PAN based fibres, [2)]pitch based fibres)

reinforcement	producer	diameter (μm)	density (gcm^{-3})	E-modulus (GPa)	tensile strength (MPa)	CTE* ($10^{-6}K^{-1}$) axial
FP α-Al_2O_3	Du Pont	20	3.9	380	> 1400	7.6
Altex alumina fibre	Sumitomo	17	3.2	300	2000	8.8
Nicalon SiC-fibre	Nippon Carbon	15	2.6	185	2700	3.5
Torayca T-300[1)]	Toray	7	1.8	230	3530	-0.26
Torayca M-40[1)]	Toray	5.5	1.8	392	2650	-1.3
Thornel P 75[2)]	Amoco	10	2.0	520	2370	-1.4
Saffil RF disk α-Al_2O_3	ICI plc.	1-5	3.3	300	2000	4.7
SiC-whiskers Silar	DWA Composites Specialities	0.6	3.2	690	6900	4.1
SiC-particles	Norton AS, ESK, Kempten	various	3.2	ca.400	-	4.7
alumina platelets	Elf, ESK, Kempten	various	3.9	ca.380	-	3.6
alumina particles	H.C. Starck, ESK, Kempten	various	4.0	ca.380	-	9.5

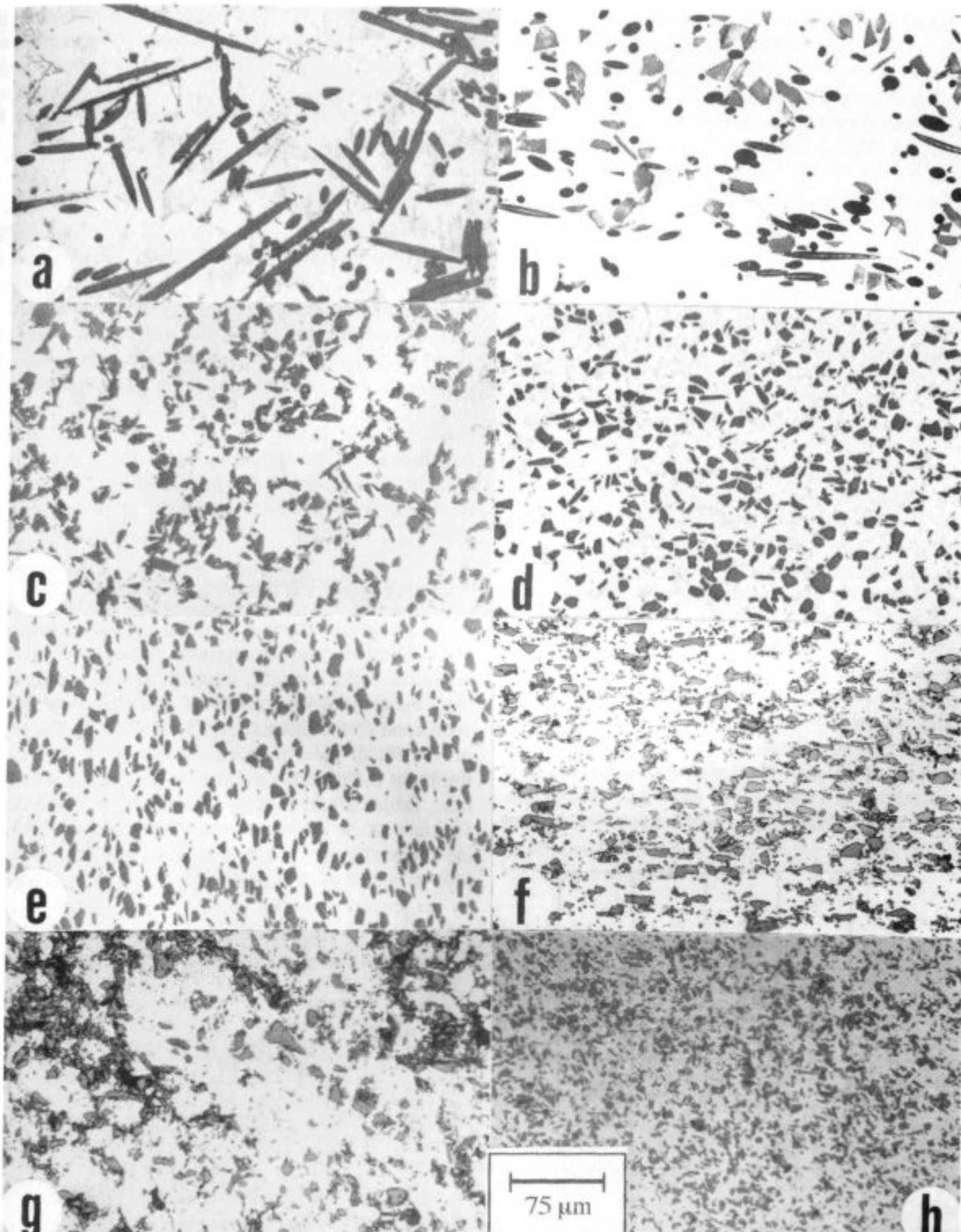

Figure 1: Collection of typical microstructures of various light metal composites as a function of reinforcement and production process.
a) Al_2O_3 short fibre reinforced magnesium,
b) Al_2O_3-SiC hybrid reinforced magnesium,
c) SiC particle reinforced aluminium (chill cast),
d) SiC particle reinforced aluminium (pressure die cast),
e) SiC particle reinforced aluminium (cast and extruded),
f) SiC particle reinforced aluminium (extruded powder blend),
g) SiC particle reinforced magnesium (spray formed),
h) SiC particle reinforced magnesium (spray formed and extruded)

- reaction infiltration of fibre or particle preforms[11,12],
- production of prematerial by stirring particles into metallic melts with subsequent sand casting, chill casting or pressure casting[2,3].

• *Powder metallurgy techniques*

- extrusion or forging of metal powder - particle mixtures[5,6],
- extrusion or forging of spray formed semi finished material[1,13,14].

• Further processing of semi finished cast material by thixocasting or forming, extrusion[15], forging, cold forming or superplastic forming,

• Joining or welding of semi finished products,

• Finishing by machining.

4 Structure and properties of light metal composites

The structure of composites is determined by the nature and shape of the reinforcing components, their distribution and orientation by the production process. Typical microstructures of various short fibre and particle reinforced light metals are shown in **Figure 1**. In the case of short fibre reinforced composites a planar isotropic distribution of the short fibres is formed as a result of the production of the fibre preform. The pressure supported sedimentation technque leads to a layer like structure (**Figures 1a & b**)[10]. The direction of infiltration is generally normal to these planes. The cast particle reinforced light metals show, depending on the working processing, typical particle distributions. Gravity cast material exhibit as a result of the casting conditions particle free regions (**Figure 1c**), whereas pressure die cast materials show a much better particle distribution (**Figure 1d**). An even distribution is achieved by extrusion of semi finished material (**Figure 1e**). An extremely homogeneous particle distribution is obtained by extrusion of mixed powders or spray formed materials (**Figures 1 f-g**).

Properties of short fibre reinforced aluminium

An increase in strength with increasing fibre content in short fibre reinforced aluminium is actually observed as the example AlSi12CuMgNi with 20 vol.% Al_2O_3 shows in **Figure 2**. Composites of light metal casting alloys is not made just to increase only the strength. The effect alone would not be justifiable economically. The improvement of the properties at high temperature with a doubling of the strength (**Figure 2**) and the rotating bending fatigue strength at 300°C (**Figure 3**), opens up possibilities for use as piston material or cylinder liners. A dramatic increase of the thermal shock resistance can be achieved at temperature of 350°C as is shown in **Figure 4**.

Properties of particle reinforced aluminium

In general addition of particles to light metals, such as magnesium and aluminium increases the elastic modulus, yield strength, ultimate tensile strength, the hardness and the wear resistance and also decreases the coefficient of the thermal expansion. The degree of improvement of these properties depends on the volume fration of the particles and the chosen means of production. **Tables 2 and 3** show a collection of properties of various particle reinforced aluminium alloys. The particle volume fraction in stirred in particle reinforced Al alloys is limited to about 20 vol.%. This limit is imposed by the process. A maximum tensile strength of over 500 MPa and E-moduli of 100 GPa are possible for this particle content. Higher particle contents can be achieved by

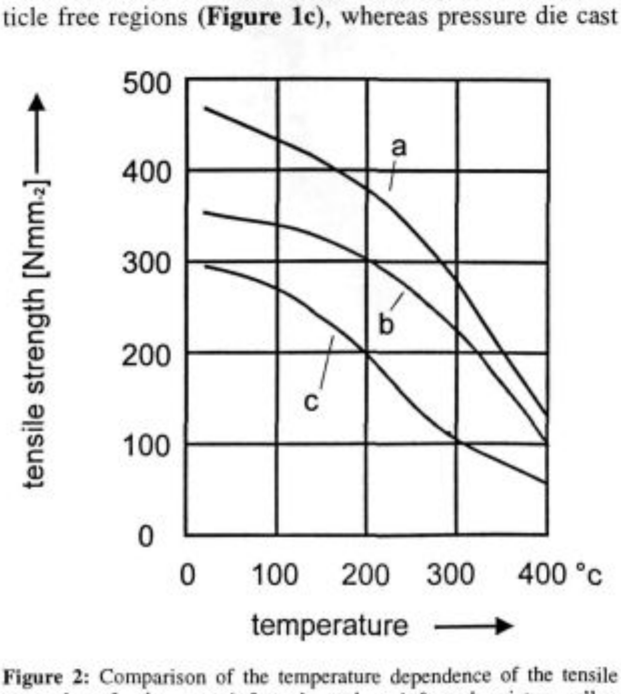

Figure 2: Comparison of the temperature dependence of the tensile strength of the unreinforced and reinforced piston alloy AlSi12CuMgNi (KS 1275)[7]
a) KS 1275 with 20 vol.% SiC whiskers,
b) KS 1275 with 20 vol.% Al_2O_3 short fibres,
c) KS 1275 unreinforced

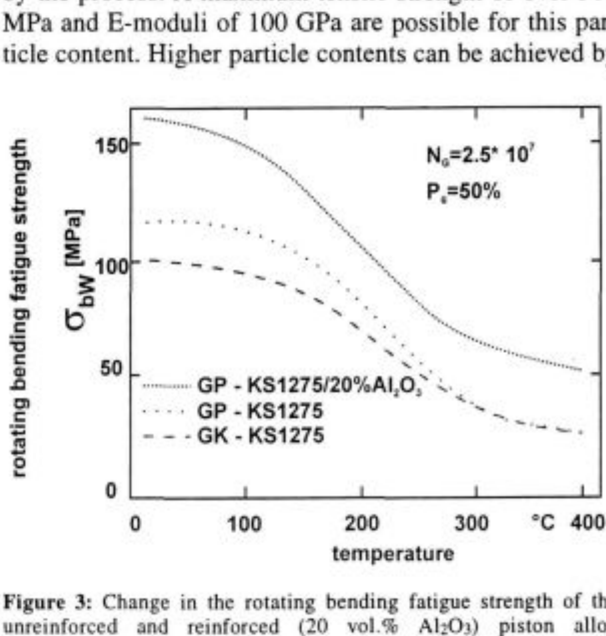

Figure 3: Change in the rotating bending fatigue strength of the unreinforced and reinforced (20 vol.% Al_2O_3) piston alloy AlSi12CuMgNi (KS 1275) with increasing temperature[8] (GK = chill cast GP = squeeze cast)

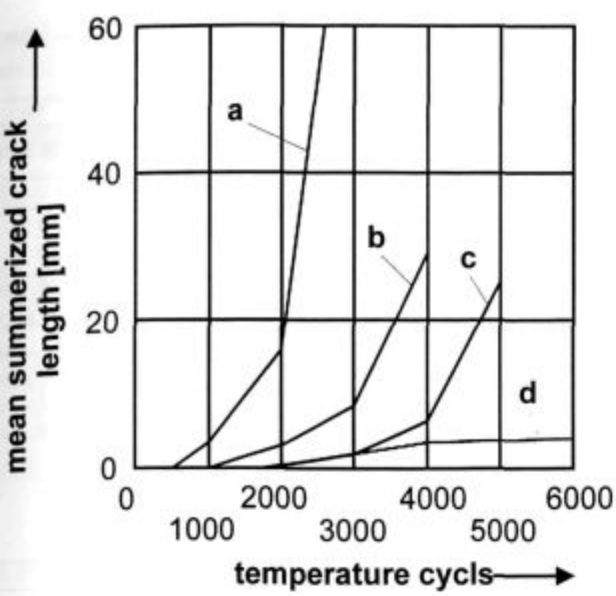

Figure 4: Temperature shock resistance of the fibre reinforced piston alloy AlSi12CuMgNi as a function of the fibre content for a temperature of 350°C[7]:
a) unreinforced,
b) 12 vol.% Al_2O_3 short fibres,
c) 17.5 vol.% Al_2O_3 short fibres,
d) 20 vol.% Al_2O_3 short fibres

infiltration of particle preforms with higher particle volume fraction. The materials then assume increasingly the characteristics of ceramics. On tensile loading premature failure occurs. The small thermal expansion is an excellant characteristic despite the metallic features.

There is a limit to the particle content of about 13-15 vol.% also for spray formed materials. The use of special alloys e.g. with lithium additions can nevertheless lead to high specific properties. If powder metallurgical technique involving extrusion and forging are applied then the particle content can be increased to more than 40 vol.%. As the result of high particle content and the resultant fine grain of the matrix very high strength of up to 760 MPa, very high E-Moduli of 125 GPa and low coefficients of expansion of 17 x $10^{-6}K^{-1}$ can be achieved. Unfortunately the elongation to fracture and the fracture toughness deteriorate. The values lie, however, in part above those for casting alloys.

Properties of discontinuously reinforced magnesium alloys

In general the strengthening effects in discontiuous reinforced composites is smaller than in continuous fibre reinforced materials but the properties are more isotropic. In the following the properties of short fibre or particle reinforced magnesium composites are listed. **Table 4** shows the 0.2 yield strength, the temperature dependence of the ultimate tensile strength and the ductility of different magnesium alloys reinforced with 20 vol.% Saffil short fibre. The properties are compared with of these of unreinforced alloys. Information about hardness, Young's modulus and coefficient of thermal expansion (CTE) are included. The results show that the main advantages of this type of composite material are the high specific strength at elevated temperatures, the increase of Young's modulus and the reduction of the CTE. The improvement of the properties depends on the volume content of the short fibres. In the range of 15 -22 vol.% short fibres the most promising properties were measured[4,16]. With a higher fibre content problems in the infiltration arises which reduces the strength and ductility of the composites.

Table 2: Selected properties of typical cast aluminium composites, prepared by chill, pressure die casting or reaction infiltration[2,3,11]. (T6 = solution annealed and aged, T5 = aged; *after ASTM G-77: cast iron 0,66 mm³; **CTE = coefficient of thermal expansion, a) after ASTM E-399 and B-645; b) after ASTM E-23), n.i. = no information

Material Identification	Composition	Yield stress (MPa)	Tensile strength (MPa)	Elongation to fracture (%)	Young's modulus (GPa)	a) Fracture toughness. b) impact strength	Wear* volume decrease (mm^3)	Thermal conductivity 22°C (cal/cm s K)	CTE** 50-100°C ($10^{-6}K^{-1}$)
Gravity casting (chill casting)						a) (MPa $m^{1/2}$)			
A356-T6	AlSi7Mg	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	n.i.	n.i.	20.7
F3S.10S-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	n.i.	n.i.	n.i.	20.2
F3K.20S-T6	AlSi10CuMgNi20SiC	372	372	0.0	101	n.i.	n.i.	0.346	17.8
Die casting					b) (J)				
A390	AlSi17Cu5Mg	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	n.i.	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	n.i.	0.384	21.4
F3N.20S-T5	AlSi10CuMnMg20SiC	338	365	0.3	108.2	0.7	0.018	0.401	16.6
Reaction infiltration		Bending strength (MPa)		Density (g/cm^3)		a) (MPa $m^{1/2}$)			
MCX-693™	Al+55-70 %	SiC	300	2.98	255	9.0	n.i.	0.430	6.4
MCX-724™	Al+55-70 %	SiC	350	2.94	226	9.4	n.i.	0.394	7.2
MCX-736™	Al+55-70 %	SiC	330	2.96	225	9.5	n.i.	0.382	7.3

Table 3: Properties of aluminium wrought alloy composites, manufactures information after[5,6,13-15]. (T6 = solution annealed and aged), *after ASTM G-77: cast iron 0,66 mm^3; **CTE = coefficient of thermal expansion, n.i. = no information.

Material Identification	Composition	Yield stress (MPa)	Tensile strength (MPa)	Elongation to fracture (%)	Young's modulus (GPa)	a) Fracture toughness. b) impact strength	Wear* volume decrease (mm^3)	Thermal conductivity 22°C (cal/cm s K)	CTE** 50-100°C ($10^{-6}K^{-1}$)
Cast starting material (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	n.i.	n.i.
Powder metallurgically prepared starting material (extruded)									
6061-T6	AlMg1SiCu	276	310	15	69.0	n.i.	n.i.	n.i.	23.0
6061-T6	+ 20% SiC	397	448	4.1	103.4	n.i.	n.i.	n.i.	15.3
6061-T6	+ 30% SiC	407	496	3.0	120.7	n.i.	n.i.	n.i.	13.8
7090-T6	AlZn8Mg2Co1.5Cu1	586	627	10.0	73.8	n.i.	n.i.	n.i.	n.i.
7090-T6	+ 30% SiC	676	759	1.2	124.1	n.i.	n.i.	n.i.	n.i.
6092-T6	AlMg1Cu1Si17.5SiC	448	510	8.0	103.0	n.i.	n.i.	n.i.	n.i.
6092-T6	AlMg1Cu1Si25SiC	530	565	4.0	117.0	20.3	n.i.	n.i.	n.i.
Spray formed starting material (extruded)									
6061-T6	+ 15% Al_2O_3	317	359	5	87.6	n.i.	n.i.	n.i.	n.i.
2618-T6	+ 13% SiC	333	450	n.i.	89.0	n.i.	n.i.	n.i.	19.0
8090-T6	AlLi2.5CuMg	480	550	n.i.	79.5	n.i.	n.i.	n.i.	22.9
8090-T6	+ 12% SiC	486	529	n.i.	100.1	n.i.	n.i.	n.i.	19.3

Table 4: Properties of short as cast fibre reinforced magnesium composites (CTE = coefficient of thermal expansion, n.d. = not determined, rt = room temperature, 0.2 YS = 0.2 yield strength, UTS = ultimate tensile strength)[4]

	Cp-Mg		AS 41		AZ 91		QE 22	
	matrix	comp.	matrix	comp.	matrix	comp.	matrix	comp.
0.2 YS (MPa) (rt)	70	220	125	240	160	230	180	250
UTS (MPa) (rt)	80	240	193	270	220	280	250	300
Elongation (%) (rt)	5.0	2.2	9.0	1.0	4.8	1.8	4.5	1.6
Young's modulus (GPa)	46	56	49.8	77.7	46	64	46	74
UTS (100°C) (MPa)	65	240	175	250	200	270	240	285
UTS (200°C) (MPa)	45	180	150	240	120	220	200	245
UTS (300°C) (MPa)	30	120	n.d.	n.d.	60	130	125	180
Vickers hardness HV10 (kp/mm^2)	40	75	n.d.	n.d.	65	140	75	125
CTE ($10^{-6}K^{-1}$)*	26.5	21.5	24.0	18.0	27.0	20.5	26.0	20.0

The second group of discontinuous reinforced composites are particle reinforced magnesium alloys. The high range of properties is achieved by the limitless variation possibilities of alloys, type of particle and production techniques. In general only a modest improvement in the strength by addition of particles is observed. But with the increase in hardness, wear resistance and Young's modulus together with the reduction of the CTE the material becomes interesting for commercial application[17]. The **Tables 5 and 6** show the propety profiles of different produced particle reinforced magnesium composites. The SiC particles used for composite materials in **Table 5** have irregular blocky shape. These particles were treated to achieve a smooth surface without sharp tips. The result are composites with high strength and very good ductility combinated with high hardness, Young's modulus and low CTE values. The P/M production technique unfluences the properties of the particle reinforced composites, as shown in **Table 6**. The highest strength but with low ductility is measured for spray formed and extruded composites. The best properties were achieved for direct powder forged composites, a near net shape production technique. With a special preform technique it is possible to produce particle or hybrid reinforced composites by squeeze casting. The properties of material system investigated are listed in **Table 5**. As reinforcement a SiC-particles-fibre hybrid preform and aluminia platelets were used. The material shows lower strength and ductility due to the solidification mi-

Table 5: Properties profile of P/M produced or squeeze cast QE 22 composites with different additions of reinforcement (SiC-particles, hybrid SiC-Al_2O_3-preforms, Al_2O_3-platelets in vol.%)[17]

	0.2 yield strength (MPa)	UTS (MPa)	Elongation to fracture (%)	Young's modulus (GPa)	Brinell hardness HB31,25/2,5	CTE rt-300°C ($10^{-6}K^{-1}$)
Powder metallurgy produced composites (T6) condition						
P/M QE 22 - T6	175	260	18	43	70	27.1
QE 22 + 10% SiC	200	265	10	48	87	21.4
QE 22 + 15% SiC	210	290	10	58	95	20.0
QE 22 + 20% SiC	225	315	6.5	66	120	18.2
QE 22 + 25% SiC	245	325	4.0	73	108	16.6
Squeeze cast composites						
Sq/C QE 22 - T6	185	262	5.2	69	48	27.0
QE 22+20%SiC hybrid	265	285	2.4	74	120	18.9
QE 22+25%SiC hybrid	270	282	1.0	80	125	17.5
QE 22 + 20% Al_2O_3 platelets	177	250	1.0	85	110	19.8

crostructure which is different to the rapid solidified structure by use of P/M technologies.

Table 6: Influence of the production technique on the properties of P/M QE 22 + 15 vol% SiC-particles-composites

	Unreinforced QE22	Spray formed and extruded	Extruded powder blends	Forged powder blends
0.2 yield strength (MPa)	180	300	250	220
UTS (MPa)	252	320	300	300
Elongation to fracture (%)	16.0	1.0	4.0	4.5
Vickers hardness (HV10 kp/mm^2)	82	92	88	94
Young's modulus (GPa)	46	69	70	79
CTE ($10^{-6}K^{-1}$)	27.1	20.5	21.1	20.8

5 Possible uses and applications for metallic matrix composites

Light metal composites are interesting materials for automobile components in the engine (*oscillating parts:* valve system, connecting rod, pistons and piston pin; *covers:* cylinder head, crankshaft main bearing; *motor block:* partially reinforced cylinder liner). An example for a successful application involving aluminium composites is the partially reinforced short fibre aluminium pistons in which the combustion chamber is reinforced with Al_2O_3 short fibres. Comparable component properties are only possible in powder metallurgical produced aluminium alloys or in iron pistons. The reason for the use of composites are, as explained above, improved high temperature properties. Similar considerations apply to partially reinforced cylinder blocks. In this case the critical areas, the bridges and cylinder surfaces are reinforced. The same applies to the reinforcement of aluminium cylinder heads where cracking in the combustion chamber is the life limiting factor. **Figure 5** shows the development goal on increasing the component temperature for reinforced aluminium cylinder heads.

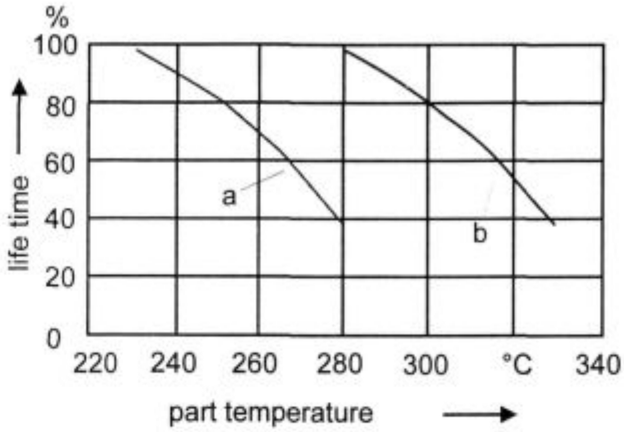

Figure 5: Component life for aluminium cylinder heads for car diesel engines (The life fimiting factor is cracking in the combustion chamber area)[7]

Potential applications can be found also in the propulsive components e.g. transverse link and particle reinforced brake discs. The latter are also employed in rail transport (tube trains, railway trains). In air and space applications, the high strength, the high E-modulus, the low thermal coefficient of expansion, the temperature stabillity and the high conductivity of reinforced light metals compared to polymer materials make composites interesting for stiffening parts, load bearing tubes, rotors, covers, and containers and supports for electronic devices. A collection of potential actual applications of the various metal matrix components (MMC's) is given in **Table 7**.

In history, the first technical applications of MMC's were in the fields of energy and information engineering, e.g. carbon brushes (Cu-graphite) or contact materials. There is still scope for further development in conductor materials, support materials for printed circuits or structures for electronic components. Further economically interesting applications are to be found in leisure applications e.g. extruded and welded particle reinforced alu-

Table 7.1: Potential and actual technological applications of metal matrix composites (part 1)

Application	Required property	Material system	Production method
automobile and commercial vehicles			
stiffeners, connecting rod, frames, piston, piston pins, valve spring retainer, brake disks, brake, brake linings, drive shaft.	high specific strength and stiffness, temperature stability, low coefficient of thermal expansion, wear resistance, thermal conductivity.	Al-SiC, Al-Al_2O_3, Mg-SiC, Mg-Al_2O_3, discontinuous reinforcements.	melt infiltration, extrusion, forging, gravity casting, pressure die casting, squeeze-casting.
accumulator plate	high stiffness, creep resistance	Pb-C, Pb-Al_2O_3	melt infiltration
military and civil aircraft			
supporting tubes, stiffeners, wings- and gear boxes, ventilation and compressor blades.	high specific strength and stiffness, temperature stability, fracture toughness, fatigue resistance	Al-B, Al-SiC, Al-C, Ti-SiC, Al-Al_2O_3, Mg-Al_2O_3, Mg-C continuous and discontinuous reinforcements.	melt infiltration, hot pressing, diffusion welding and soldering, extrusion, squeeze-casting.
turbine blade	high specific strength and stiffness, temperature stability, fracture toughness, fatigue resistant.	W, superalloys, intermetallics e.g. Ni_3Al, Ni-Ni_3Nb	melt infiltration, directional solidification of near net shape components

Table 7.2: Potential and actual technological applications of metal matrix composites (Part 2)

Application	Required property	Material system	Production method
space			
frames, stiffeners, antennas, joints, bolds.	high specific strength and stiffness, temperature stability, low coefficient of thermal expansion, thermal conductivity	Al-SiC, Al-B, Mg-C, Al-C, Al-Al_2O_3, continuous and discontinuous reinforcements.	melt infiltration, extrusion, diffusion bonding and joining (spatial structures)
energy engineering (electrical contacts and conductive material)			
carbon brushes	high electrical and thermal conductivity wear resistance	Cu-C	melt infiltration, powder metallurgy.
electrical contacts	high electrical conductivity, temperature and corrosion resistance, switch capacity, resistance to burn.	Cu-C, Ag-Al_2O_3, Ag-C, Ag-SnO_2, Ag-Ni	melt infiltration, powder metallurgy, extrusion, hot pressing
superconductor	superconductivity, mechanical strength, ductility.	Cu-Nb, Cu-Nb_3Sn, Cu-YBaCO	extrusion, powder metallurgy, coating techniques.
other applications			
spot welding electrodes	resistance to burn.	Cu-W	powder metallurgy, infiltration.
bearings	load bearing capacity, wear resistance.	Pb-C, bronze-Teflon	powder metallurgy, infiltration

minium-mountain bike frames and golf clubs with particle reinforced inserts. Baseball bats are another possible application because the higher damping would result in a completely different striking behaviour.

6 Recycling

The necessity of integrating production waste and scrap of newly developed materials is of particular importance. Since ceramic materials are used in the form of particles, short fibres or continuous fibres as reinforcement it is not possible to separate the components with aim of reutilising of matrix *and* the reinforcement. But conventional melting techniques can be employed to recover the matrix alloy. In the case of cast or powder metallurgically produced discontinuously reinforced light metals (short fibre or particle) it is possible under certain conditions to reuse the swarf. This is particular so for particle reinforced aluminium casting alloys where no problems arise by remelting the swarf and directly use of the cast ingots without modification. The paper[18] provides an overview of the various recycling concepts for light alloy matrix composites taking into account alloy composition, reinforcement type and the production and working history.

7 Conclusion

The development of metal matrix composites can be used to improve critical properties of metal alloys e.g. high temperature strength, stiffness, wear resistance and thermal expansion. With high variability of materials combination and manufacturing techniques it is possible to produce tailor-made materials. Which combination and production techniques are choosen depends on the requirement of the possible application. The production processes allow the manufacture of semi-finished products or near net shape parts.

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