Metal Matrix Composites

Custom-made Materials for Automotive and Aerospace Engineering

Edited by
Karl U. Kainer

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The Editor

Prof. K. U. Kainer
GKSS Forschungszentrum
Institut für Werkstoffforschung
Max Planck-Str. 1
21502 Geesthacht
Germany
karl.kainer@gkss.de

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Preface

Metal matrix composites can no longer be excluded from daily life. The individual consumer is not aware of the variety of material systems and their application; in many cases they are even unknown. Examples are carbides for machining of materials in product engineering, noble metal composite systems for contacts in electronics and electro-technology, copper–graphite sliding contacts for generators and electric motors and multicompound systems for brake linings in high speed brakes. After the massive effort in recent years to develop metal matrix composites (MMCs) with light metal matrixes the successful application of these materials has taken place in traffic engineering, especially in automotive and transport technology. New applications are, for example, partially fiber-reinforced pistons and hybrid reinforced crank cases in passenger cars and truck engines, and particle-reinforced brake discs for light trucks, motorcycles, passenger cars and rail-mounted vehicles. A further application area of these materials is in civil and military air and space flight. These innovative materials are of great interest for modern material applications due to the possibility to develop MMCs with specific properties. Ongoing from this potential, the metal matrix composites meet the desired concepts of the design engineer, because they represent custom-made materials. This material group is becoming of interest for construction and functional materials, if the property profile of conventional materials does not meet the requirement of lightweight construction. The advantages of metal matrix composites are of use if a meaningful cost–performance relationship is possible during production of the components. Of special economic and ecological interest is the need for integration of processing residues, cycle scrap and waste products from these materials into the material cycle.

In the area of communication and power engineering, the replacement of the currently dominant structural materials with functional materials based on nonferrous and noble metals is a development aim. For example, good electrical and thermal properties combined with high strength and wear resistance are demanded. Although the application of metal matrix composites in the area of contact materials has been known for years, it has been necessary to carry out further optimization for the use of new or modified material systems. Of special interest are materials which are able to dissipate the heat which develops during the use of electrical and electronic units (heat sinks). Additional requirements concerning the effect of temperature on resistance are development challenges. In many cases improvements in wear resistance will be of benefit, leading to the development of multifunctional material systems.

This book gives an overview of the current state of research and development as well as a realistic introduction to materials in various application areas. Besides basic knowledge of metal matrix composites, the idea of appropriate material systems and production and processing methods, special importance is attached to the presentation of the potential of materials and their application possibilities. This summary arose from a further education seminar of the same name, presented by the German Society of Material Science, which has taken place regularly since 1990. Because of the overview character of the book it is addressed to engineers, scientists and technicians in the material development, production and design areas. As the editor I would like to thank all the authors for their efforts in providing appropriate articles. A special thanks to the publisher Wiley-VCH, represented by Dr. Jörn Ritterbusch, for the support grants and excellent supervision, especially necessary in the critical phases.

Geesthacht, December 2005

Prof. Dr.-Ing. habil. Karl Ulrich Kainer

Contents

List of Contributors

H. Biermann
Institute for Materials Engineering
Technische Universität
Bergakademie Freiberg
Gustav-Zeuner-Str. 5
09599 Freiberg
Germany

C. Blawert
Centre of Magnesium Technology
GKSS Research Centre Geesthacht
GmbH
Max-Planck-Straße 1
21502 Geesthacht
Germany

M. Buschka
Faculty of Mechanical Engineering
Department of Machining Technology
University of Dortmund
Baroper Straße 301
44227 Dortmund
Germany

R. Buschmann
Thermal Ceramics de France
Route de Lauterbourg BP 148
67163 Wissembourg
France

H. Dieringa
Centre of Magnesium Technology
GKSS Research Centre Geesthacht
GmbH
Max-Planck-Straße 1
21502 Geesthacht
Germany

A. Feldhoff
Universität Hannover
Institut für Physikalische Chemie und
Elektrochemie
Callinstraße 3-3A
30167 Hannover
Germany

O. Hartmann
Robert Bosch GmbH
Robert-Bosch-Straße 40
96050 Bamberg
Germany

N. Hort
Centre of Magnesium Technology
GKSS Research Centre Geesthacht
GmbH
Max-Planck-Straße 1
21502 Geesthacht
Germany

K. U. Kainer
Centre of Magnesium Technology
GKSS Research Centre Geesthacht GmbH
Max-Planck-Straße 1
21502 Geesthacht
Germany

E. Köhler
KS Aluminum Technology AG
Hafenstraße 25
74172 Neckarsulm
Germany

P. Krug
PEAK Werkstoff GmbH
Siebeneiker Straße 235
42553 Velbert
Germany

M. Lange
Faculty of Mechanical Engineering
Department of Machining Technology
University of Dortmund
Baroper Straße 301
44227 Dortmund
Germany

J. Niehues
KS Aluminum-Technology AG
Hafenstraße 25
74172 Neckarsulm
Germany

E. Pippel
Max-Planck-Institut für
Mikrostrukturphysik
Weinberg 2
06120 Halle
Germany

J. Schmidt
Head of R&D Department
NAGEL Maschinen- und
Werkzeugfabrik GmbH
Oberboihinger Straße 60
72622 Nuertingen
Germany

G. Sinha
PEAK Werkstoff GmbH
Siebeneiker Straße 235
42553 Velbert
Germany

A. Wank
Department of Composite Materials
Technical University of Chemnitz
Straße der Nationen 62
09107 Chemnitz
Germany

K. Weinert
Faculty of Mechanical Engineering
Department of Machining Technology
University of Dortmund
Baroper Straße 301
44227 Dortmund
Germany

B. Wielage
Department of Composite Materials
Technical University of Chemnitz
Straße der Nationen 62
09107 Chemnitz
Germany

J. Wilden
Department of Manufacturing
Engineering
Technical University of Ilmenau
Neuhaus 1
98693 Ilmenau
Germany

J. Woltersdorf
Max-Planck-Institut für
Mikrostrukturphysik
Weinberg 2
06120 Halle
Germany

1
Basics of Metal Matrix Composites

Karl Ulrich Kainer

1.1
Introduction

Metal composite materials have found application in many areas of daily life for quite some time. Often it is not realized that the application makes use of composite materials. These materials are produced *in situ* from the conventional production and processing of metals. Here, the Dalmatian sword with its meander structure, which results from welding two types of steel by repeated forging, can be mentioned. Materials like cast iron with graphite or steel with a high carbide content, as well as tungsten carbides, consisting of carbides and metallic binders, also belong to this group of composite materials. For many researchers the term metal matrix composites is often equated with the term light metal matrix composites (MMCs). Substantial progress in the development of light metal matrix composites has been achieved in recent decades, so that they could be introduced into the most important applications. In traffic engineering, especially in the automotive industry, MMCs have been used commercially in fiber reinforced pistons and aluminum crank cases with strengthened cylinder surfaces as well as particle-strengthened brake disks.

These innovative materials open up unlimited possibilities for modern material science and development; the characteristics of MMCs can be designed into the material, custom-made, dependent on the application. From this potential, metal matrix composites fulfill all the desired conceptions of the designer. This material group becomes interesting for use as constructional and functional materials, if the property profile of conventional materials either does not reach the increased standards of specific demands, or is the solution of the problem. However, the technology of MMCs is in competition with other modern material technologies, for example powder metallurgy. The advantages of the composite materials are only realized when there is a reasonable cost – performance relationship in the component production. The use of a composite material is obligatory if a special property profile can only be achieved by application of these materials.

The possibility of combining various material systems (metal – ceramic – nonmetal) gives the opportunity for unlimited variation. The properties of these new materials are basically determined by the properties of their single components. Figure 1.1 shows the allocation of the composite materials into groups of various types of materials.

The reinforcement of metals can have many different objectives. The reinforcement of light metals opens up the possibility of application of these materials in areas where weight reduction has first priority. The precondition here is the improvement of the component properties. The development objectives for light metal composite materials are:

- Increase in yield strength and tensile strength at room temperature and above while maintaining the minimum ductility or rather toughness,
- Increase in creep resistance at higher temperatures compared to that of conventional alloys,
- Increase in fatigue strength, especially at higher temperatures,
- Improvement of thermal shock resistance,
- Improvement of corrosion resistance,
- Increase in Young's modulus,
- Reduction of thermal elongation.

To summarize, an improvement in the weight specific properties can result, offering the possibilities of extending the application area, substitution of common materials and optimisation of component properties. With functional materials there is another objective, the precondition of maintaining the appropriate function of the material. Objectives are for example:

- Increase in strength of conducting materials while maintaining the high conductivity,
- Improvement in low temperature creep resistance (reactionless materials),
- Improvement of burnout behavior (switching contact),
- Improvement of wear behavior (sliding contact),
- Increase in operating time of spot welding electrodes by reduction of burn outs,
- Production of layer composite materials for electronic components,
- Production of ductile composite superconductors,
- Production of magnetic materials with special properties.

For other applications different development objectives are given, which differ from those mentioned before. For example, in medical technology, mechanical properties, like extreme corrosion resistance and low degradation as well as biocompatibility are expected.

Although increasing development activities have led to system solutions using metal composite materials, the use of especially innovative systems, particularly in the area of light metals, has not been realised. The reason for this is insufficient process stability and reliability, combined with production and processing problems and inadequate economic efficiency. Application areas, like traffic engineering, are very cost orientated and conservative and the industry is not willing to pay additional costs for the use of such materials. For all these reasons metal matrix composites are only at the beginning of the evolution curve of modern materials, see Fig. 1.2.

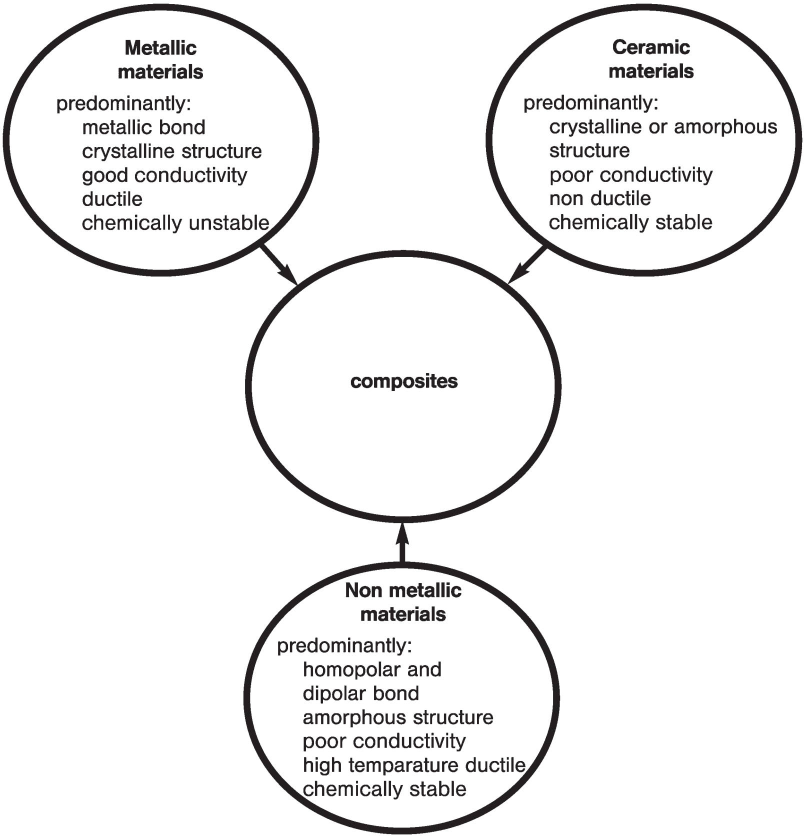

Fig. 1.1 Classification of the composite materials within the group of materials [1].

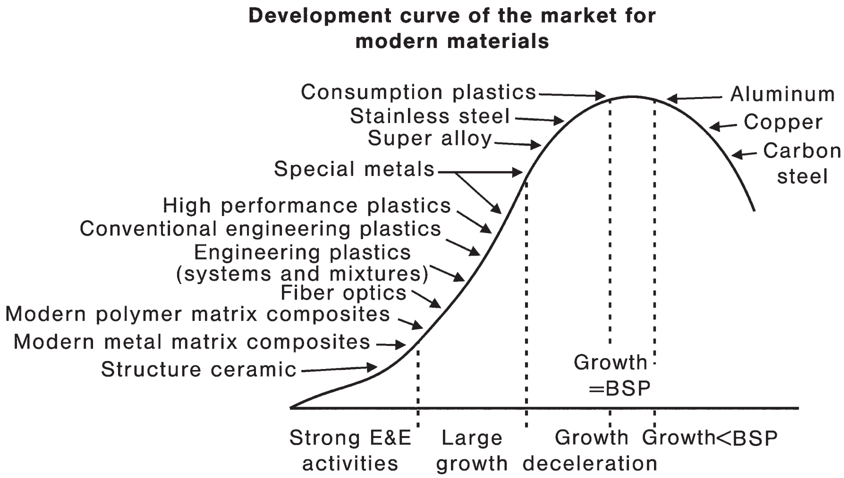

Fig. 1.2 Development curve of the market for modern materials [2].

Metal matrix composites can be classified in various ways. One classification is the consideration of type and contribution of reinforcement components in particle-, layer-, fiber- and penetration composite materials (see Fig. 1.3). Fiber composite materials can be further classified into continuous fiber composite materials (multi- and monofilament) and short fibers or, rather, whisker composite materials, see Fig. 1.4.

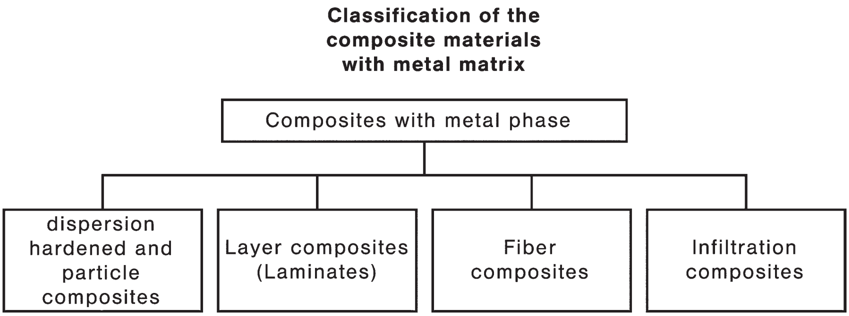

Fig. 1.3 Classification of composite materials with metal matrixes.

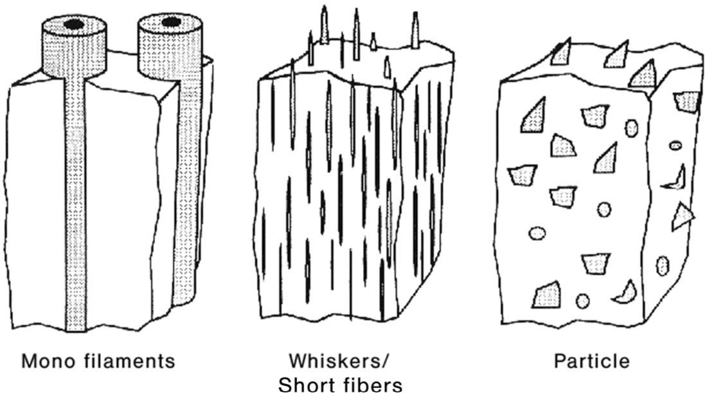

Fig. 1.4 Schematic presentation of three shapes of metal matrix composite materials [3].

1.2 Combination of Materials for Light Metal Matrix Composites

1.2.1 Reinforcements

Reinforcements for metal matrix composites have a manifold demand profile, which is determined by production and processing and by the matrix system of the composite material. The following demands are generally applicable [4]:

- low density,
- mechanical compatibility (a thermal expansion coefficient which is low but adapted to the matrix),
- chemical compatibility,
- thermal stability,
- high Young's modulus,
- high compression and tensile strength,
- good processability,
- economic efficiency.

These demands can be achieved only by using non-metal inorganic reinforcement components. For metal reinforcement ceramic particles or, rather, fibers or carbon fibers are often used. Due to the high density and the affinity to reaction with the matrix alloy the use of metallic fiber usual fails. Which components are finally used, depends on the selected matrix and on the demand profile of the intended application. In Refs. [4, 5] information about available particles, short fibers, whiskers and continuous fibers for the reinforcement of metals is given, including data of manufacturing, processing and properties. Representative examples are shown in Table 1.1. The production, processing and type of application of various reinforcements depends on the production technique for the composite materials, see Refs. [3, 7]. A combined application of various reinforcements is also possible (hybrid technique) [3, 8].

Every reinforcement has a typical profile, which is significant for the effect within the composite material and the resulting profile. Table 1.2 gives an overview of possible property profiles of various material groups. Figure 1.5 shows the specific strength and specific Young's modulus of quasi-isotropic fiber composite materials with various matrixes in comparison to monolithic metals. The group of discontinuous reinforced metals offers the best conditions for reaching development targets; the applied production technologies and reinforcement components, like short fibers, particle and whiskers, are cost effective and the production of units in large item numbers is possible. The relatively high isotropy of the properties in comparison to the long-fiber continuous reinforced light metals and the possibility

Tab. 1.1 Properties of typical discontinuous reinforcements for aluminium and magnesium reinforcements [6].

Reinforcement	*Saffil (Al_2O_3)*	*SiC particle*	*Al_2O_3 particle*
crystal structure	δ-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

Tab. 1.2 Property potential of different metal matrix composites, after [2].

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

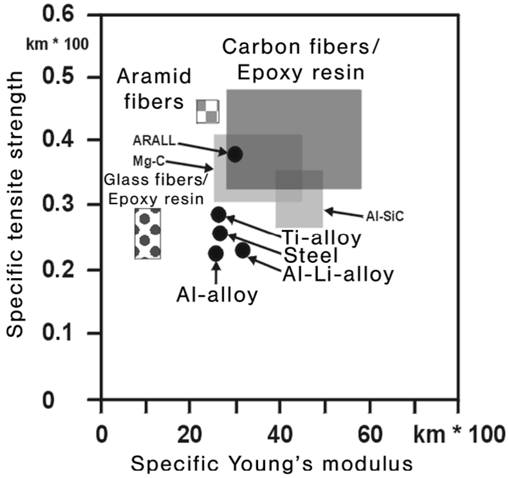

Fig. 1.5 Specific tensile strength and specific Young's modulus of different quasi-isotropic fiber composite materials in comparison to some metal alloys, after [2].

of processing of composites by forming and cutting production engineering are further advantages.

1.2.2
Matrix Alloy Systems

The selection of suitable matrix alloys is mainly determined by the intended application of the composite material. With the development of light metal composite materials that are mostly easy to process, conventional light metal alloys are applied as matrix materials. In the area of powder metallurgy special alloys can be applied due to the advantage of fast solidification during the powder production. Those systems are free from segregation problems that arise in conventional solidification. Also the application of systems with oversaturated or metastable structures is possible. Examples for matrix configurations are given in Refs. [7, 9–15]:

- conventional cast alloys
  - G-AlSi12CuMgNi
  - G-AlSi9Mg
  - G-AlSi7 (A356)
  - AZ91
  - AE42
- conventional wrought alloys
  - AlMgSiCu (6061)
  - AlCuSiMn (2014)
  - AlZnMgCu1.5 (7075)
  - TiAl6V4
- special alloys
  - Al–Cu–Mg–Ni–Fe-alloy (2618)
  - Al–Cu–Mg–Li-alloy (8090)
  - AZ91Ca

For functional materials non-alloyed or low-alloyed non-ferrous or noble metals are generally used. The reason for this is the demand for the retention of the high conductivity or ductility. A dispersion hardening to reach the required mechanical characteristics at room or higher temperatures is then an optimal solution.

1.2.3 Production and Processing of Metal Matrix Composites

Metal matrix composite materials can be produced by many different techniques. The focus of the selection of suitable process engineering is the desired kind, quantity and distribution of the reinforcement components (particles and fibers), the matrix alloy and the application. By altering the manufacturing method, the processing and the finishing, as well as by the form of the reinforcement components it is possible to obtain different characteristic profiles, although the same composition and amounts of the components are involved. The production of a suitable precursor material, the processing to a construction unit or a semi-finished material (profile) and the finishing treatment must be separated. For cost effective reasons prototypes, with dimensions close to the final product, and reforming procedures are used, which can minimize the mechanical finishing of the construction units.

In general the following product engineering types are possible:

- Melting metallurgical processes
  - infiltration of short fiber-, particle- or hybrid preforms by squeeze casting, vacuum infiltration or pressure infiltration [7, 13–15]
  - reaction infiltration of fiber- or particle preforms [16, 17]
  - processing of precursor material by stirring the particles in metallic melts, followed by sand casting, permanent mold casting or high pressure die casting [9, 10]

- Powder metallurgical processes
  - pressing and sintering and/or forging of powder mixtures and composite powders
  - extrusion or forging of metal-powder particle mixtures [11, 12]
  - extrusion or forging of spraying compatible precursor materials [7, 18, 19]
- Hot isostatic pressing of powder mixtures and fiber clutches
- Further processing of precursor material from the melting metallurgy by thixocasting or -forming, extrusion [20], forging, cold massive forming or super plastic forming
- Joining and welding of semi-manufactured products
- Finishing by machining techniques [21]
- Combined deformation of metal wires (group superconductors).

Melting metallurgy for the production of MMCs is at present of greater technical importance than powder metallurgy. It is more economical and has the advantage of being able to use well proven casting processes for the production of MMCs. Figure 1.6 shows schematically the possible methods of melting metallurgical production. For melting metallurgical processing of composite materials three procedures are mainly used [15]:

- compo-casting or melt stirring
- gas pressure infiltration
- squeeze casting or pressure casting.

Both the terms compo-casting and melt stirring are used for stirring particles into a light alloy melt. Figure 1.7 shows the schematic operational sequence of this procedure. The particles are often tend to form agglomerates, which can be only dissolved by intense stirring. However, here gas access into the melt must be absolutely avoided, since this could lead to unwanted porosities or reactions. Careful attention must be paid to the dispersion of the reinforcement components, so that the reactivity of the components used is coordinated with the temperature of the melt and the duration of stirring, since reactions with the melt can lead to the dissolution of the reinforcement components. Because of the lower surface to volume ratio of spherical particles, reactivity is usually less critical with stirred particle reinforcement than with fibers. The melt can be cast directly or processed with alternative procedures such as squeeze casting or thixocasting. Melt stirring is used by the Duralcan Company for the production of particle-strengthened aluminum alloys [9, 10]. At the Lanxide Company a similar process is used, with additional reactions between the reinforcement components and the molten matrix being purposefully promoted to obtain a qualitatively high-grade composite material [16]. In the reaction procedures of the Lanxide Company it may be desirable that the reinforcement component reacts completely with the melt to form the component *in situ*, which then transfers the actual reinforcement effect to the second phase in the MMC.

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. The melting