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0521483573 - An Introduction to Metal Matrix Composites
T. W. Clyne and P. J. Withers
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General introduction

After more than a quarter of a century of active research, composites based on metals are now beginning to make a significant contribution to industrial and engineering practice. This is partly a consequence of developments in processing methods. However, equally important have been advances in the understanding of various structure–property relationships, assisting in the identification of cost effective solutions and highlighting important objectives in the control of microstructure and the design of components. In this first chapter, a brief overview is given of the nature of MMCs and the background to their development.

1.1 Types of MMC and general microstructural features

The term metal matrix composite (MMC) encompasses a wide range of scales and microstructures. Common to them all is a contiguous metallic matrix[†]. The reinforcing constituent is normally a ceramic, although occasionally a refractory metal is preferred. The composite microstructures may be subdivided, as depicted in Fig. 1.1, according to whether the reinforcement is in the form of continuous fibres, short fibres or particles. Further distinctions may be drawn on the basis of fibre diameter and orientation distribution. Before looking at particular systems in detail, it is helpful to identify issues relating to the microstructure of the final product. A simplified overview is given in Table 1.1 of the implications for composite performance of the main microstructural features. Whereas some of these microstructural parameters are readily pre-specified, others can be very difficult to control. Necessarily, the

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[†] A further sub-class is that in which the matrix is an intermetallic compound, but such materials are not wholly within the scope of this book.

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Table 1.1 *Overview of structure/property relationships for MMCs. The symbols indicate whether an increase in the microstructural parameter in the left-hand column will raise, lower or leave unaffected the properties listed. Also shown are the section numbers within the book where the trends concerned are covered in detail.*

	Composite property					
Microstructural feature	α_{axial}	E_{axial}	Tensile YS (0.2% PS)	Work hardening rate	Creep resistance	Toughness (ductility)
Ceramic content f	⇓ § 5.1.2	⇑ §3.6	⇑ §4.1.1	⇑ §4.3.1	⇑ §5.2.3	⇓ §7.3.3
Fibre aspect ratio s	⇓ §5.1.2	⇑ §3.6	⇑ or ⇓ §4.1.1	⇑ §4.3.1	⇑ §5.2.3	⇑ or ⇓ §7.4.2
Misalignment $g(\theta)$	⇑ §5.1.2	⇓ §3.6	⇑ or ⇓ §7.1.2	⇓ §4.3.1	⇓ §5.2.3	⇑ or ⇓ §7.4.2
Fibre diameter d	–	–	⇓ §4.2	⇓ §4.3.2	⇑ §5.2.3	⇑ §7.4.3
Inhomogeneity of f	–	–	–	–	⇓ §5.2.3	⇓ §7.4.5
Bond strength τ_i	⇓	⇑ §6.1.4	⇑	⇑ §4.4.2	⇑ §5.2.3	⇑ or ⇓ §6.1.4
Reaction layer t	⇑ or ⇓	⇓ §6.3.2	⇓ §6.1.4	⇓ §6.1.4	⇓ §5.2.3	⇓ §6.1.4
$\Delta\alpha\,\Delta T$ stresses	–	–	⇓ §4.1.2	⇓ §4.1.2	⇓ §5.2.3	⇓ §7.2.2
Matrix porosity	⇓ §5.1.1	⇓ §3.6	⇓	⇓	⇓	⇓ §7.3.3
Matrix YS	–	–	⇑ §4.2	⇑ §4.3.2	⇑ §5.2.3	⇓ §7.4.6

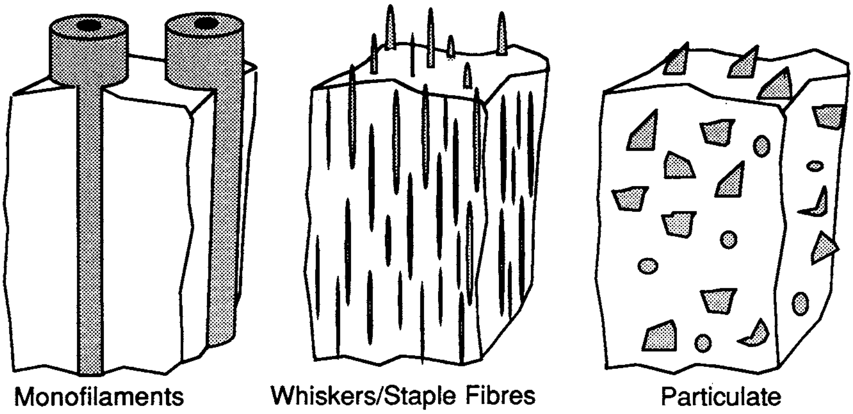

Fig. 1.1 Schematic depiction of the three types of MMC, classified according to the type of reinforcement.

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interplay between microstructure and properties is much more complex than the representation shown, which also conceals various uncertainties. Nevertheless, it is important to identify simple microstructural objectives and methods for attaining them before embarking on the design and fabrication of any specific component. One of the aims of this book is to help with that task.

An important lesson learnt in connection with polymeric composites (PMCs) is that the material specification and the component design must be integrated into a single operation. For MMCs, the high formability of the matrix (particularly when compared with polymer resins) means that this need not be the case, or that it is only partially true. Several types of discontinuously reinforced MMC material are available in stock form, such as billet, rod and tube, suitable for various secondary fabrication operations. Even long fibre MMC stock material can sometimes be subjected to certain shaping and forming operations. This highlights the potential versatility of MMCs, but it should nevertheless be recognised that, in common with PMCs, they are essentially anisotropic, potentially to a much greater extent than unreinforced metals. Unlike aligned polymer-based composites, however, excellent axial performance can be combined with transverse properties which are more than satisfactory. The freedom to separate material preparation and component design/production procedures, in much the same way as with unreinforced metals, presents both an opportunity and a potential pitfall. Certainly, there will be many instances where the integration of these operations is likely to assist in optimisation of the use of MMCs.

1.2 Historical background

Examples of metal matrix composites stretch back to the ancient civilisations. Copper awls from Cayonu (Turkey) date back to about 7000 BC and were made by a repeated lamination and hammering process, which gave rise to high levels of elongated non-metallic inclusions[1]. Among the first composite materials to attract scientific as well as practical attention were the dispersion hardened metal systems. These developed from work in 1924 by Schmidt[2] on consolidated mixtures of aluminium/alumina powders and led to extensive research in the 1950s and 1960s[3]. The principles of precipitation hardening in metals date from the 1930s[4,5] and were developed in the following decade[6,7]. Recent collected papers[8,9], celebrating such landmarks in the use of metals, give a fascinating insight into the major metallurgical advances during this period.

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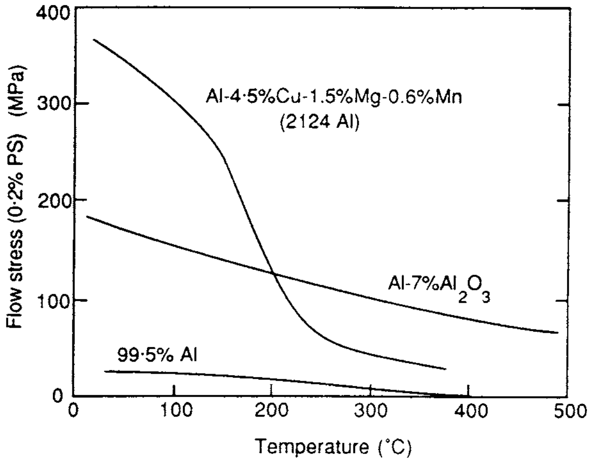

Fig. 1.2 Variation with temperature of the flow stress of three aluminium-based materials[3], illustrating the retention of dispersion strengthening to temperatures above which hardening precipitates coarsen or dissolve.

For both dispersion hardening and precipitation hardening, the basis of the strengthening mechanism is to impede dislocation motion with small particles. This is achieved by the incorporation of either fine oxide particles or non-shearable precipitates within a metallic matrix. Of prime importance in this context is the minimisation of the spacing between the inclusions. Since it is generally possible to achieve finer distributions in precipitation hardened systems, these normally exhibit higher strengths at room temperature. However, dispersion strengthened systems show advantages at elevated temperature, because of the high thermal stability of the oxide particles (Fig. 1.2). While extremely low volume fractions are desirable in terms of ductility, dispersoid contents as high as 15 vol% have been used in applications requiring good high temperature strength and creep resistance. Creep is effectively suppressed because the dislocations must climb over the dispersoids by diffusive processes and this results in creep rates decreasing with increasing dispersoid size.

More recent developments have brought the concept of metal matrix composites closer to engineering practice. An interesting example is provided by the so-called 'dual phase' steels, which evolved in the 1970s[10]. These are produced by annealing fairly low carbon steels in the $\alpha + \gamma$ phase field and then quenching so as to convert the γ phase to martensite. The result is a product very close to what is now referred to as a particulate

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MMC, with about 20% of very hard, relatively coarse martensite particles distributed in a soft ferrite matrix. This is a strong, tough and formable material, now used extensively in important applications such as car bodywork. Its success could be interpreted as confirming the viability of the particulate MMC concept, although its properties have not often been considered in terms of composite theory.

Interest in fibrous metal matrix composites mushroomed in the 1960s, with effort directed mainly at aluminium and copper matrix systems reinforced with tungsten and boron fibres. In such composites the primary role of the matrix is to transmit and distribute the applied load to the fibres. High reinforcement volume fractions are typical (~40–80%), giving rise to excellent axial performance. Consequently, matrix microstructure and strength are of secondary importance. Research on continuously reinforced composites waned during the 1970s, largely for reasons of high cost and production limitations. The continuing need for high temperature, high performance materials for various components in turbine engines has triggered a resurgence of interest, mainly directed towards titanium matrices. As mentioned in §12.2.9, attention has focused on hoop-wound unidirectional systems. Factors such as thermal fatigue (§5.3.3), interfacial chemical stability (§6.3.1) and thermal shock resistance (§8.1.5) have become of equal importance to those of straightforward mechanical performance.

Discontinuously reinforced composites fall somewhere between the dispersion strengthened and fibre strengthened extremes, in that both matrix and reinforcement bear substantial proportions of the load. They have been rapidly developed during the 1980s, with attention focused on Al-based composites reinforced with SiC particles and Al_2O_3 particles and short fibres. The combination of good transverse properties, low cost, high workability and significant increases in performance over unreinforced alloys has made them the most commercially attractive system for many applications (Chapter 12). They are distinguished from the dispersion hardened systems, of which they are a natural extension, by the fact that, because the reinforcement is large (~1–100 μm), it makes a negligible contribution to strengthening by Orowan inhibition of dislocation motion (Fig. 1.3). In addition, since the volume fraction is relatively high (5–40%), load transfer from the matrix is no longer insignificant (Chapters 3 and 4). However, unlike continuously reinforced systems, the matrix strength, as affected by precipitation and dislocation strengthening (§4.2, §4.3.2, §10.1 and §10.2), also plays an important role.

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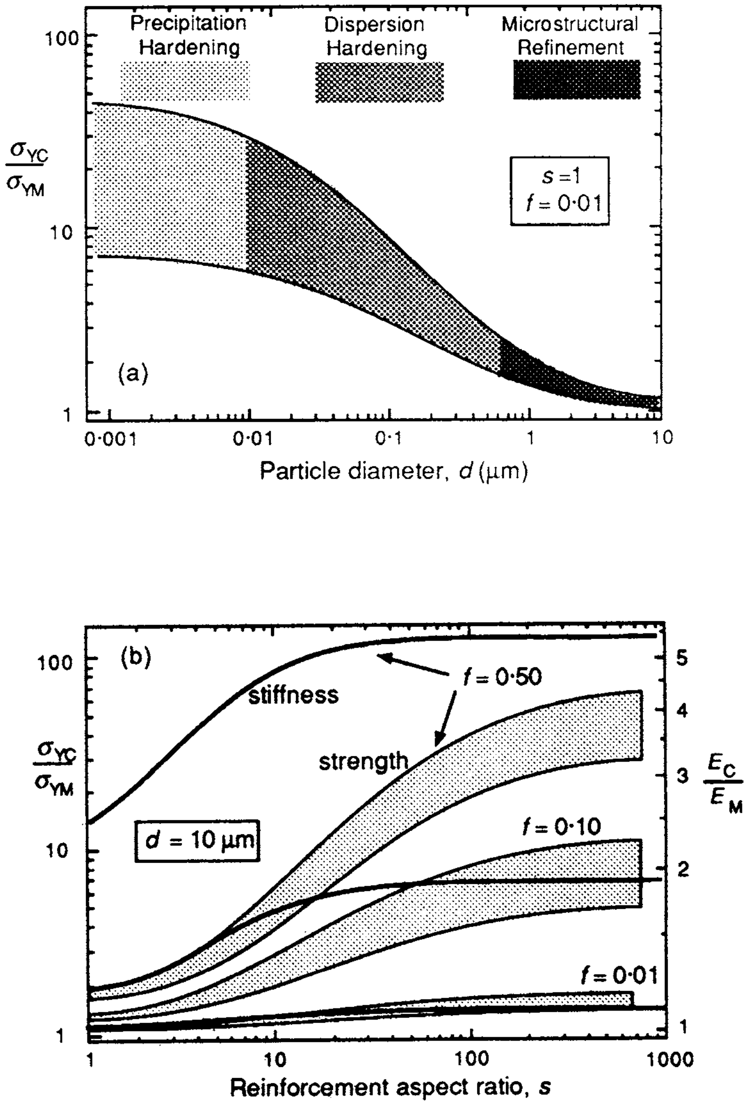

Fig. 1.3 Schematic illustration of the magnitude and range of operation of the primary composite strengthening mechanisms as a function of inclusion shape, size and volume fraction. In (a), matrix strengthening dominates, with the inclusions constituting too low a volume fraction to carry a significant proportion of the load. In (b), strengthening and stiffening are primarily a consequence of load transfer to the reinforcement. In some cases, both types of mechanism may be significant, as with particle reinforcement of age-hardening alloys. Furthermore, the reinforcement may itself give rise to both types of strengthening, directly by load transfer and indirectly by stimulating changes in matrix microstructure.

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1.3 Interactions between constituents and the concept of load transfer

One definition (Longman's dictionary) of the word 'composite' is simply: 'something combining the typical or essential characteristics of individuals making up a group'. Central to the philosophy behind the use of any composite material is the extent to which the qualities of two distinct constituents can be combined, without seriously accentuating their shortcomings. In the context of MMCs, the objective might be to combine the excellent ductility and formability of the matrix with the stiffness and load-bearing capacity of the reinforcement, or perhaps to unite the high thermal conductivity of the matrix with the very low thermal expansion of the reinforcement.

In attempting to identify attractive matrix/reinforcement combinations, it is often illuminating to derive a 'merit index' for the performance required, in the form of a specified combination of properties. Appropriate models can then be used to place upper and lower bounds on the composite properties involved in the merit index, for a given volume fraction of reinforcement. The framework for such predictions has been clearly set out by Ashby[11], and an example of a composite property map is shown in Fig. 1.4. This graph refers to a merit index for the minimisation of thermal distortion during heating or cooling. Plotted on a field of expansivity against conductivity, this merit index will be high at bottom right and low at top left. The data shown therefore indicate that the resistance of aluminium to thermal distortion can be improved by the incorporation of silicon carbide, but will be impaired if boron nitride is added.

In practice, there is often interest in establishing composite properties to a greater precision than is possible by the use of bounds, which in many cases are widely separated. This can be relatively complex, particularly for MMCs – in which certain matrix properties may be significantly affected by the presence of the reinforcement. Much of this book is thus devoted to understanding, through an examination of the relevant thermophysical interactions, the principles underlying effective hybridisation of this type. Rules will be developed governing mechanical loadings (Chapters 2, 3, 4 and 7), thermal expansion (§5.1), thermal/electrical conductivity (§8.1) and other more complex properties such as wear resistance (§8.2) and damping capacity (§8.3). In many of these areas, the role of the interface is critical and Chapter 6 is devoted to interfacial phenomena and their effects on composite behaviour.

Central to an understanding of the mechanical behaviour of a

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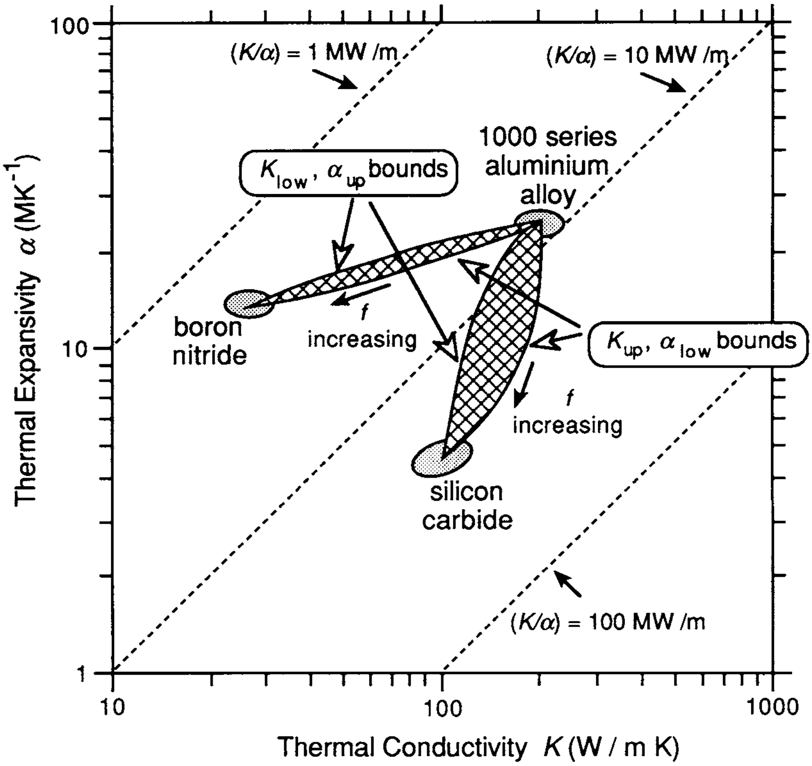

Fig. 1.4 Predicted map[11] of thermal expansivity, α, against thermal conductivity, *K*, for composites made up of either silicon carbide or boron nitride in an aluminium matrix. The diagonal dotted lines represent constant values of a merit index, given by K/α, taken as indicative of the resistance to thermal distortion. The shaded areas, defined by upper and lower bounds of the two parameters (obtained from appropriate equations), indicate the possible combinations of *K* and α expected for Al–SiC and Al–BN composites, depending on the volume fraction, shape and orientation distribution of the reinforcement.

composite is the concept of load sharing between the matrix and the reinforcing phase. The stress can vary sharply from point to point, but the proportion of the external load borne by each of the individual constituents can be gauged by volume-averaging the load within them. Of course, at equilibrium, the external load must equal the sum of the volume-averaged loads borne by the constituents[†] (e.g. the matrix and

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[†] In the absence of an externally applied load, the individual constituents may still be stressed (due to the presence of residual stresses), but these must balance each other according to eqn (1.1).

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the reinforcement). This gives rise to the condition

$$(1 - f)\bar{\sigma}_{\mathrm{M}} + f\bar{\sigma}_{\mathrm{I}} = \sigma^{\mathrm{A}} \tag{1.1}$$

governing the volume-averaged matrix and inclusion (fibre or particle) stresses ($\bar{\sigma}_{\mathrm{M}}, \bar{\sigma}_{\mathrm{I}}$) in a composite under an external stress σ^{A}, containing a volume fraction f of reinforcement. (In the most general form of eqn (1.1), $\bar{\sigma}_{\mathrm{M}}$, $\bar{\sigma}_{\mathrm{I}}$ and σ^{A} are tensors.) Thus, for a simple two-constituent MMC under a given applied load, a certain proportion of that load will be carried by the reinforcement and the remainder by the matrix. Provided the response of the composite remains elastic, this proportion will be independent of the applied load and it represents an important characteristic of the material. As is examined in later chapters, it depends on the volume fraction, shape and orientation of the reinforcement and on the elastic properties of both constituents. The reinforcement may be regarded as acting efficiently if it carries a relatively high proportion of the externally applied load. This can result in higher strength, as well as greater stiffness, because the reinforcement is usually stronger, as well as stiffer, than the matrix. The concept of elastic load transfer has been entirely familiar to those working with (polymer-based) fibre composites over the past 30–40 years. It is readily translated to the elastic behaviour of MMCs, although calculation of the load partitioning is often more complex as a result of the greater interest in discontinuous (short fibre and particulate) reinforcement, as opposed to continuous fibres (Chapters 2 and 3).

While stiffening is well understood, confusion occasionally arises when considering the origin of strengthening, in the sense that the strengthening contribution arising from load transfer is sometimes attributed to enhanced *in situ* matrix strengthening and vice versa (Fig. 1.3). Both types of strengthening are discussed in Chapter 4. As with unreinforced metals, MMCs are expected to be able to sustain a certain amount of plastic deformation in normal service. It is particularly important, therefore, that their stress–strain response beyond the elastic limit be well understood. In practice, at least for discontinuously reinforced MMCs, both load transfer and the effect of the presence of the reinforcement on the *in situ* properties of the matrix need to be invoked in order to explain the observed behaviour. The latter can often be predicted using well-established laws and correlations drawn from dislocation theory and metallurgical experience. Treatment of the load transfer, however, is a little more problematical – particularly when the matrix starts to undergo plastic deformation. In the present book, considerable use is made of an

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analytical method of predicting load transfer – the Eshelby technique (see Chapter 3). Central to this approach is the concept of the ***misfit strain*** – i.e. the difference between the 'natural' shape of the reinforcement and the 'natural' shape of the hole it occupies in the matrix[†]. Equations can be derived to predict the load transfer for any misfit strain – such as can arise from the difference in stiffness of the two constituents (Chapter 3), from differential thermal contraction (Chapter 5) or from plastic deformation of the matrix (Chapter 4). (The same phenomena can also be simulated using numerical methods – see Chapter 2, but the accessibility of an analytical technique facilitates the study of general trends.)

Finally, to complicate the issue a little further, even a rigorous treatment of load transfer and an appreciation of the *in situ* yielding and work hardening behaviour of the matrix does not give the complete picture. Frequently, an applied stress can cause the reinforcement to start to carry a very high load indeed. For example, even a small amount of matrix plasticity creates a relatively large misfit strain and hence transfers load very strongly to the reinforcement. Such load transfer may not be sustainable. For example, with discontinuous reinforcement it would require very high local stresses in certain regions of the matrix and interface. Under these circumstances, stress relaxation phenomena (such as interfacial sliding or diffusion) will tend to occur (Chapter 4), which act to reduce the load borne by the reinforcement and hence to impair the load-bearing capacity of the composite as a whole. These stress relaxation processes are difficult to model accurately, but at least their effect can be understood and predicted for well-characterised material under specific conditions.

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[†] 'Natural' in this context means the shape that the constituent would have if the other constituent(s) were not present.

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