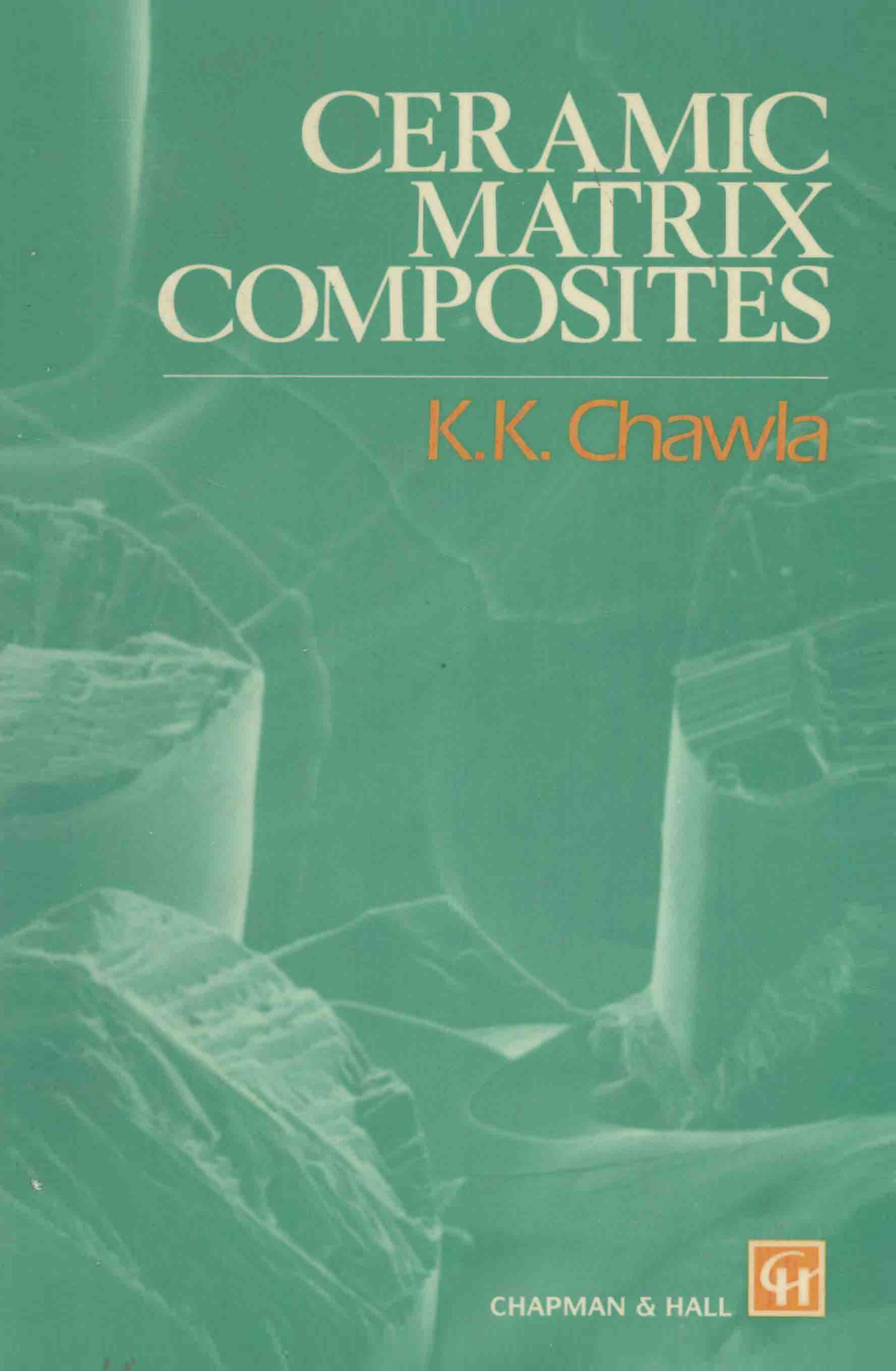

CERAMIC MATRIX COMPOSITES

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Ceramic Matrix Composites

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Ceramic Matrix Composites

तमसो मा ज्योतिर्गमय

Lead me from darkness to light

To
Kanika, Nikhilesh and Nivedita
for putting up with him and it, once more

Preface

Materials science and engineering (MS&E) is by its very nature an interdisciplinary activity. Researchers from a wide variety of disciplines, metallurgy, ceramics, physics, chemistry, mechanics, electrical and electronic engineering, etc. can and do participate in the MS&E activities. The need and desirability of such an interdisciplinary effort is understandable inasmuch as advanced or high-performance materials are critical for any of the modern industries. It is almost a given axiom that progress in any field (energy, building materials, transportation, electronics, aerospace, electric power, consumer products, etc.) depends on the availability of suitable materials having specific characteristics. In this regard, let me quote from another work of mine:

> It is a truism that technological development depends on advances in the field of materials. One does not have to be an expert to realize that a most advanced turbine or aircraft design is of no use if adequate materials to bear the service loads and conditions are not available. Whatever the field may be, the final limitation on advancement depends on materials [1].

It is pertinent to quote from some other sources about a fundamental change that is occurring in the materials field:

> A fundamental reversal in the relationship between human beings and materials [has occurred]. Its economic consequences are likely to be profound. Historically humans have adapted such natural materials as stone, wood, clay, vegetable fiber and animal tissue to economic uses. The smelting of metals and the production of glass represented a refinement in this relationship. Yet it is only recently that advances in the theoretical understanding of the structure of physical and biological matter, in experimental technique and in processing technology have made it possible to ***start with a need and then develop a material to meet***... [2].

And:

> ...the classical model of materials application has been inverted. We once sought applications for materials. We now have applications driving the creation of materials. We now design materials for what we need [3].

Designing materials for specific applications is, indeed, the underlying philosophy of composite materials. The materials marketplace is increasingly becoming a highly competitive arena where substitution of traditional materials by engineered materials is the norm; quality and value added to the material as well as the energy cost are critical in the final cost. A study by the US National Research Council [4] has emphasized in no uncertain terms the importance of synthesis, processing, characterization and performance of materials for success in the international marketplace. Add to this the ever-important public demand for a clean and healthy environment, and one can easily realize how important the whole material life cycle of a given component is. I wish to emphasize the item of environmental impact of the new materials and processes, including the recyclability of materials. Ultimately, the engineered materials must last longer, reduce material waste, be more energy efficient. I believe that composite materials can contribute to a safe and healthy environment.

Although metals, ceramics and polymers make the three legs of what might be called the tripod of MS&E, increasingly it is becoming evident that the lines of demarcation between traditional disciplines such as metallurgy, ceramics and polymers are getting quite blurry. Consider the following. Ceramic materials are being made from polymeric precursors, metals are being produced with a glassy rather than crystalline structure while semicrystalline polymers are finding commercial applications. This intermingling of materials is most evident in the field of composite materials where one has the ultimate objective of tailoring a material having a specific set of characteristics starting from components having different characteristics. Tying together process and microstructural control to the desired performance goals in the final component or product is the ultimate goal. In fact, it is now recognized on all hands that in order to meet the diverse and exacting demands, materials must be ***engineered*** at every step. In this regard, mother nature has an abundance of lessons for us. Materials in nature are tailored over a very large spectrum of length scale, from atomic or molecular level to micro to macroscopic dimensions. Some very interesting examples of nature's work can be found in collagen-based composite materials such as skin, cartilage, bone, sea shells, etc. Nature has designed these composites for multifunctional applications requiring sometimes flexibility and strength and at other times resistance to various environments.

The theme of this book is: processing, structure, properties and performance of ceramic matrix composites. My definition of the ceramic matrix is rather broad for the purposes of this book. It includes inorganic silica-based glasses, crystalline ceramics, glass-ceramics, intermetallics, and that very special material, in elemental form, called carbon. All of these have an implicit unifying thread in that they are fairly high-temperature structural materials. This, I believe, is the first dedicated text on the subject of ceramic matrix composites. There are, of course, many conference proceedings or multi-author books available on the subject, for example, references 5 and 6. In this book, I have excluded cement and similar building materials, mainly because they are not high-temperature structural materials. For anyone interested in the topic of fiber-reinforced cement-based composites, there are books available on the subject [7, 8].

The plan of the book is as follows. After an introductory chapter, we first examine ceramic **matrix** materials (Chapter 2) and the processing, microstructure and properties of **reinforcement** (Chapter 3). Inasmuch as rather dramatic developments have occurred in the area of ceramic fibrous reinforcements, Chapter 3 is rather large. This is followed by **processing** of ceramic matrix composites (Chapter 4). We examine the **interface** region in CMCs, in some detail, in Chapter 5. **Properties** of ceramic matrix composites are then examined in detail in Chapters 6 through 10. Chapter 6 describes the micromechanical aspects of elastic, physical and thermal properties. Chapter 7 gives a description of the mechanical behavior of composites: monotonic, fatigue and creep. Chapter 8 gives a thorough description of thermal stresses in composites. The important subject of interface mechanics and the various mechanisms that can be exploited to obtain improved toughess in a ceramic matrix composite are discussed in Chapter 9. This is followed by a discussion of laminated composites in Chapter 10. Finally, I discuss the various **applications and performance**-related topics in Chapter 11. I have tried to derive every important relationship not requiring very complex mathematical treatments.

I have aimed this book at the final-year undergraduate and first-year graduate students in materials science and engineering as well as the practicing engineer or scientist. I have used portions of the material contained in this text for a senior undergraduate course, a first-year graduate course, and in short courses for engineers from the industry. The response was very heartening. I hope that the book will also obtain the same response from a much broader audience. Except for the very basic ideas of materials science and engineering, I have assumed very little prior knowledge of any special kind on the part of the reader that is required to follow the material. The book may thus appear to be rather pedantic, at places, to the more experienced reader. I apologize for that. There are plenty of references and suggested reading material for the reader who wants to dig deeper. I have provided problems at the end of each chapter in the hope that by solving them, the reader will add to her/his understanding of the material in the text.

There remains the pleasant task of acknowledging a number of people without whose valuable input, tangible and intangible, this work would not have been possible. In alphabetical order, they are: A. Choudhury, M.K. Ferber, F. Gerstle, J.R. Hellmann, J.C. Hurt, O.T. Inal, M.G. Jenkins, B.A. MacDonald, T.A. Michalske, J.M. Rigsbee, P.K. Rohatgi, S. Suresh, K. Upadhya, and A.K. Vasudevan. An immense debt of gratitude is owed to S.G. Fishman and R. Pohanka, my program managers at the US Office of Naval Research, for their understanding, patience and encouragement over the years. I should also like to thank my graduate students and post-doctoral research associates whose work has contributed to my understanding of the subject matter. The ones who stand out in this group are: J.S. Ha, R. Venkatesh, R.U. Vaidya and Z.R. Xu. Portions of the text were read and commented upon by N. Chawla, V. Gupta, E. Kroshe, T.A. Parthasarathy, R.U. Vaidya and Z.R. Xu. I am truly thankful to these people for important feedback. I am also very thankful to the following for their generous hospitality during my sabbatical in 1992–93: J. Cohen, Y.-P. Chung, I. Daniel, K.T. Faber, M.E. Fine, S.P. Shah and J.R. Weertman (all at Northwestern University, Evanston, IL), B. Ilschner and F. Rezaï-Aria (Ecole Polytechnique, Lausanne, Switzerland).

Thanks are also due to my family members, Nivi, Nikhil and Kanika, for understanding my compulsion to undertake such time-consuming ventures. That is the intangible part. They also rendered more tangible help in sorting things out, preparation of figures, copy-editing and indexing. As always, I can never thank enough my parents, Manohar Lal and Sumitra Chawla, for their selflessness, constant encouragement and inspiration. I have always considered the book-writing assignments that I have undertaken as educational in nature. This one was no exception. In this regard, I wish to record my appreciation of N. Hancox and M. Dunn for inviting me to undertake this work.

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A Note to the Reader

In this text, I have followed the standard American usage. This will be immediately evident in the spellings of certain words such as fiber, center, behavior, etc. rather than fibre, centre, behaviour, respectively. In general, compound words are not hyphenated. Prefixes such as co, pre, semi are closed up with the word they modify. For example, pushout rather than push-out, preexisting rather than pre-existing, etc. However, I have left the spellings unchanged in the journal title in a reference or a book title in a citation. While I have bowed to the American usage in the language of the text, I have rigourously followed the Système International (SI) units. This stems from my belief that sooner rather than later the American scientists, engineers and industry will be using SI units. The widespread use of SI units in the US has suffered a long delay. The scientific merits of the SI units are overwhelming. If not the scientific merits of the SI units, then the force of economic necessity will do the job. By using SI units, I am hereby contributing my mite in that the direction. I am, however, fully cognizant that one should be able to convert from one system of units to another. Hence, detailed information on this topic is given in Appendix B.

Contents

Introduction

1

A composite material is a material that has a chemically and/or physically distinct phase distributed within a continuous phase. The composite generally has characteristics better than or different from those of either component. The matrix phase is the continuous phase, while the distributed phase, commonly called the reinforcement phase, can be in the form of particles, whiskers or short fibers, continuous fibers or sheet. Figure 1.1 shows the types of composite based on the form of reinforcement. Oftentimes it is convenient to classify different types of composite as per the matrix material

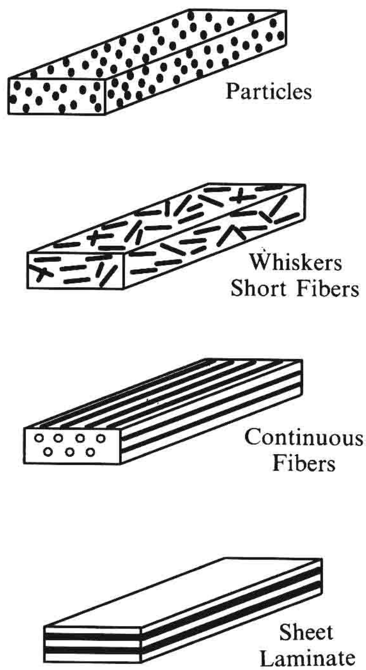

Fig. 1.1 Types of composite based on the form of reinforcement.

characteristics, e.g. polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs). Figure 1.2 shows this schematically. The reinforcement in any matrix can be polymeric, metallic or ceramic. Polymeric matrix composites containing reinforcement fibers such as carbon, glass or aramid are quite commonly used as engineering materials. Metals containing ceramic particles, whiskers or fibers (short or long) are also gaining in importance. The ceramic matrix composites are the newest entrants in the composites field.

The choice of individual components, in regard to their synthesis and chemical composition, that make up a composite, the processing required to produce that composite, and the mechanical behavior of the composite, are factors of obvious importance to the ultimate performance of the composite. However, an additional and very important factor that enters in the evaluation of the performance of a composite is the presence of an interface region between matrix and reinforcement, which can occupy a rather large area. We discuss the importance of interface in Chapter 5 and elsewhere in the book. Suffice it to say here that control of the interface characteristics is the key to designing composites having an optimum set of properties. Figure 1.3 shows how the ultimate performance of a composite is linked to these factors.

The subject matter of this book is ***ceramic matrix composites***. The term ceramics covers a wide variety of inorganic materials, which are generally non-metallic and are frequently processed at high temperatures. In view of

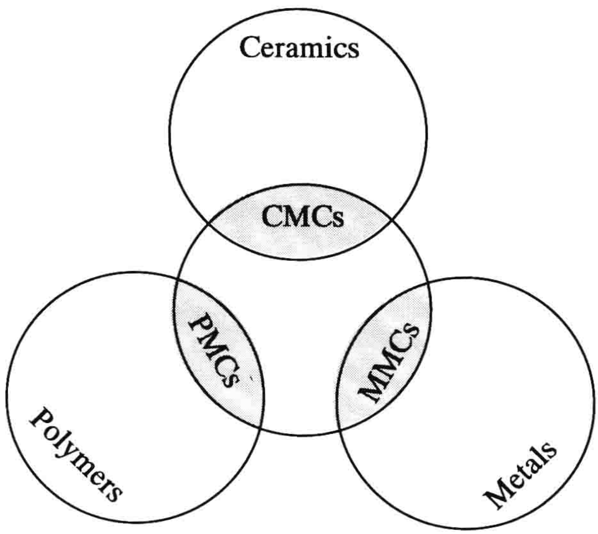

Fig. 1.2 Types of composite based on the matrix material, polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs).

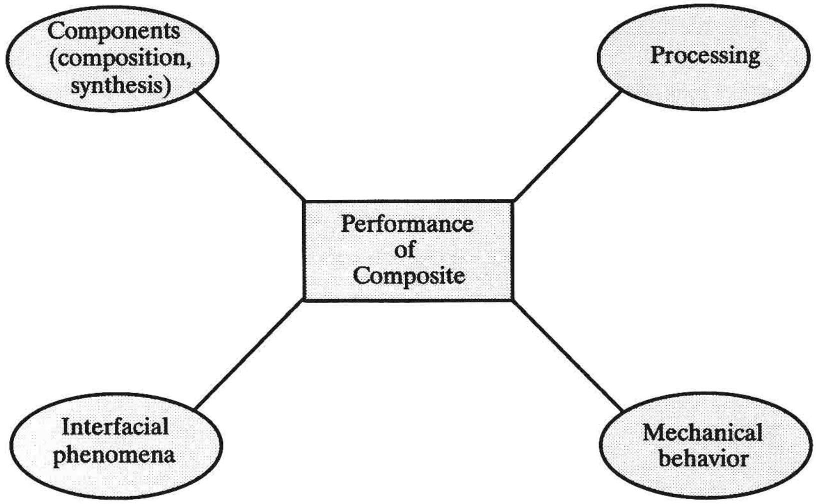

Fig. 1.3 Performance of a composite is linked to some important factors: composition of components, their mechanical behavior, processing and the characteristics of the interface between matrix and reinforcement.

the advances made in the last quarter of the 20th century, it is convenient to categorize the ceramic materials into the following two classes:

1. Traditional or conventional ceramics: these are generally in monolithic form. These include bricks, pottery, tiles and a variety of art objects.
2. Advanced or high-performance ceramics: these represent a new and improved class of ceramic materials where, frequently, some sophisticated chemical processing route is used to obtain them. Generally, their characteristics are a sensitive function of the high quality and purity of the raw materials used. Examples of these high-performance ceramics include oxides, nitrides and carbides of silicon, aluminum, titanium and zirconium.

Table 1.1 lists some important high-performance ceramic materials. An

Table 1.1 Properties of some important ceramic materials

Material	*Young's modulus* $E(GPa)$	*Poisson's ratio* ν	*Thermal expansion coefficient* $\alpha(10^{-6}\,K^{-1})$
SiC	480	0.3	4
Al_2O_3	380	0.25	8
Cordierite	130	0.25	2
Mullite	215	0.25	5
Sodalime glass	70	0.23	9

important characteristic of these advanced ceramics is their unusually high resistance to heat, chemicals, abrasion and wear. These very characteristics, however, make them difficult to fabricate in a simple and economical way. It is this class of high-performance ceramics that is commonly used in making ceramic marix composites. Monolithic high performance ceramics combine some very desirable characteristics, e.g. high strength and hardness, excellent high-temperature capability, chemical inertness, wear resistance and low density. They are, however, not very good under tensile and impact loading, and, unlike metals, they do not show any plasticity and are prone to catastrophic failure under mechanical or thermal loading (***thermal shock***). We characterize this difference in the behavior of metals and ceramics by saying that metals are forgiving while ceramics are not forgiving. The forgiving nature of metals has its source in the high mobility of dislocations in them, which allows them to deform plastically before fracture. Plastic deformation being an energy-absorbing process, the fracture process in metals involves extensive energy dissipation. The absence of such an energy-dissipating phenomenon in ceramics causes them to fail in a catastrophic fashion, i.e. makes them unforgiving. Understandably, some of the major effort of the materials community in the field of structural materials over the last quarter of the 20th century has been directed toward incorporating a variety of energy-dissipating phenomena in the fracture process of ceramics, i.e. imparting them a damage-tolerant behavior. Despite significant advances in toughness enhancement of monolithic ceramics, it is my view that ceramic matrix composites represent a quantum leap in that direction. In this book we shall explore this important topic in some detail.

1.1 CERAMICS *VIS-À-VIS* OTHER MATERIALS

It is instructive to compare the use or service temperature of different types of material. It is the maximum temperature at which a material can be used for an extended period. Figure 1.4 compares the approximate service temperature ranges of some important polymers, metals and ceramics. Clearly, ceramics are the only class of materials viable at very high temperatures. As mentioned above, ceramics also have higher hardness, strength and elastic modulus than metals and polymers. They also have lower density, thermal expansion coefficient and thermal and electrical conductivity. In particular, the characteristics of low density and low thermal expansion of ceramics assume a great deal of importance in most applications. Density and thermal expansion coefficients of some materials of interest are shown in Figs 1.5 and 1.6, respectively. The greatest drawback of ceramics *vis-à-vis* metals is their extremely low fracture toughness, which in practice means that these materials have a very low tolerance of crack-like defects. The symbol K_{Ic}, having the units of MPa $m^{1/2}$ called

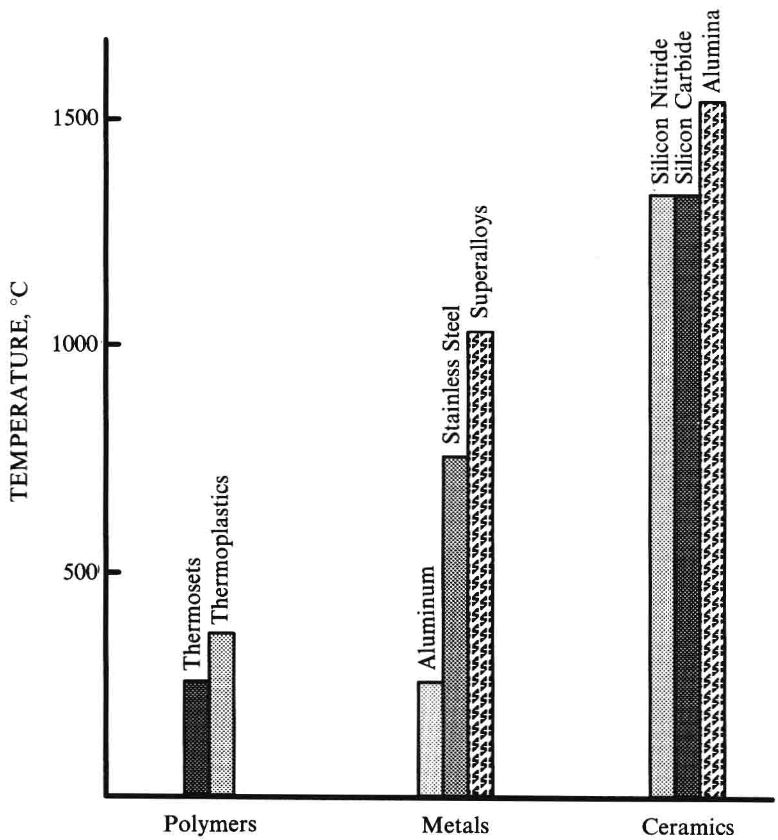

Fig. 1.4 Service temperature limit (indicative) of polymers, metals and ceramics.

fracture toughness, is used to denote this characteristic of materials. Table 1.2 gives some typical values. Note the characteristically low values of fracture toughness of ceramics. One can try to minimize the quantity of structural defects in ceramics and also ensure that they are smaller than a certain critical size by careful control of the raw materials and processing. However, any preexisting defects can grow to a critical size in service because of mechanical and thermal loading, environment, etc.; and, consequently, a catastrophic fracture ensues. Therefore, a critical need exists for increasing the toughness of ceramics. Also of importance is the need to improve the in-service reliability of ceramics. This has to do with the flaw size and flaw distribution. Beyond a shadow of doubt, minimizing the pernicious problem of catastrophic fracture in ceramics is a very important goal. Let us examine this concept of fracture toughness and see how mother nature might have some interesting lessons for us in this area. As Hillig [1]

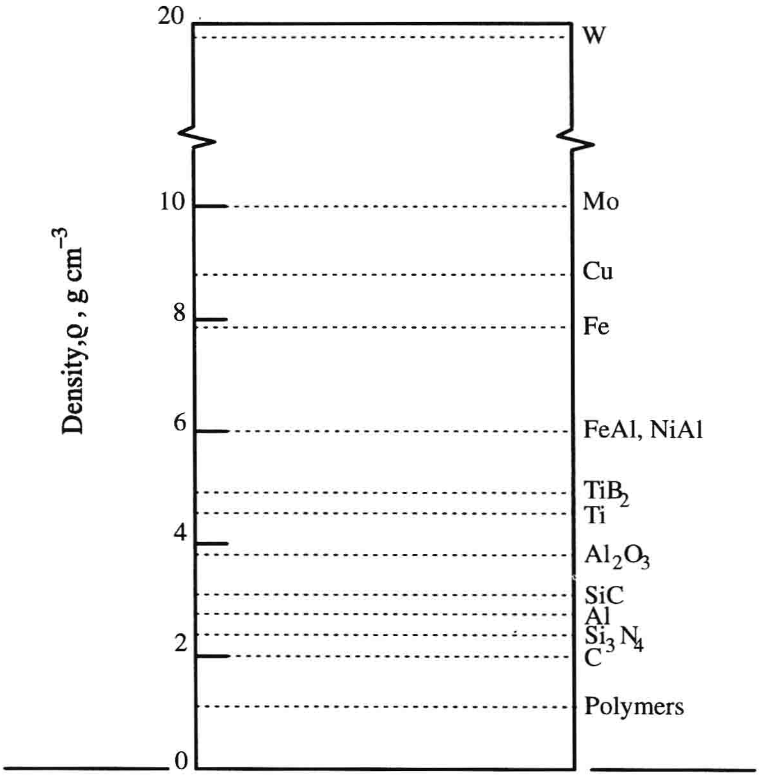

Fig. 1.5 Density of some materials.

points out, strong winds (50–80 km h^{-1}) can snap trees and poles like matchsticks. A birch tree, however, can get away with the loss of only a few leaves. The reason for this is that its trunk is strong and resilient. Under the action of a gale, the tops of young birch trees can bend as much as 45°. This high degree of resilience or compliance in a birch tree results from the appropriate ply architecture that nature provides. This resilience is what we call toughness in more scientific parlance. The low toughness of ceramic materials also manifests itself in another form, i.e. strength of ceramics has a very high degree of sensitivity to the presence and size of flaws such as cracks, voids, inclusions, etc.

Improving the toughness of ceramic materials is thus a major objective. One of the important approaches to attain this goal is via ceramic matrix composites. As should be clear from the discussion above, high performance ceramics must have superior structural and/or mechanical characteristics because they find application in some very demanding environments, e.g. rocket nozzles, heat exchangers, automobile engines and cutting tools. Yet