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Composite Materials

Science and Engineering

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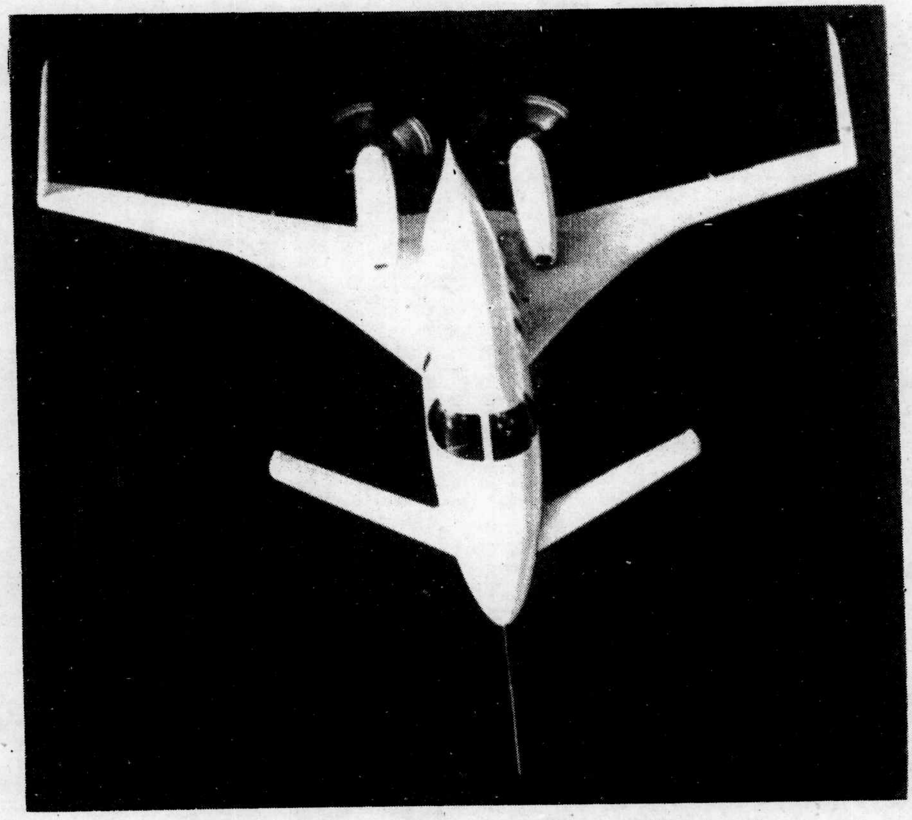

Beechcraft Starship 1: An almost all composite aircraft
(Courtesy of Beech Aircraft Corporation)

Preface

The subject of composite materials is truly an inter- and multidisciplinary one. People working in fields such as metallurgy and materials science and engineering, chemistry and chemical engineering, solid mechanics, and fracture mechanics have made important contributions to the field of composite materials. It would be an impossible task to cover the subject from all these viewpoints. Instead, we shall restrict ourselves in this book to the objective of obtaining an understanding of composite properties (e.g., mechanical, physical, and thermal) as controlled by their structure at micro- and macrolevels. This involves a knowledge of the properties of the individual constituents that form the composite system, the role of interface between the components, the consequences of joining together, say, a fiber and matrix material to form a unit composite ply, and the consequences of joining together these unit composites or plies to form a macrocomposite, a macroscopic engineering component as per some optimum engineering specifications. Time and again, we shall be emphasizing this main theme, that is structure–property correlations at various levels that help us to understand the behavior of composites.

In Part I, after an introduction (Chap. 1), fabrication and properties of the various types of reinforcement are described with a special emphasis on microstructure–property correlations (Chap. 2). This is followed by a chapter (Chap. 3) on the three main types of matrix materials, namely, polymers, metals, and ceramics. It is becoming increasingly evident that the role of the matrix is not just that of a binding medium for the fibers but it can contribute decisively toward the composite performance. This is followed by a general description of the interface in composites (Chap. 4). In Part II a detailed description is given of some of the important types of composites, namely, polymer matrix composites (Chap. 5), metal matrix composites (Chap. 6), ceramic composites (Chap. 7), carbon fiber composites (Chap. 8), and multifilamentary superconducting composites (Chap. 9). The last two are described separately because they are the most advanced fiber composite systems of the 1960s and 1970s. Specific characteristics and applications of these composite systems are brought out in these chapters. Finally, in Part III, the micromechanics (Chap. 10) and macromechanics (Chap. 11) of composites are described in detail, again emphasizing the theme of how structure (micro and macro) controls the properties. This is followed by a description of strength and fracture modes in composites (Chap. 12). This chapter also describes some salient points of difference, in regard to design, between conventional and fiber composite materials. This is indeed of fundamental importance in view of the fact that composite materials are not just any other new material. They represent a total departure from the way we are used to handling conventional monolithic materials, and, consequently, they require unconventional approaches to designing with them.

Throughout this book examples are given from practical applications of composites in various fields. There has been a tremendous increase in applications of composites in sophisticated engineering items. Modern aircraft industry readily comes to mind as an ideal example. Boeing Company, for example, has made widespread use of structural components made of "advanced" composites in 757 and 767 planes. Yet another striking example is that of the Beechcraft Company's Starship 1 aircraft (see frontispiece). This small aircraft (8–10 passengers plus crew) is primarily made of carbon and other high-performance fibers in epoxy matrix. The use of composite materials results in 19% weight reduction compared to an identical aluminum airframe. Besides this weight reduction, the use of composites made a new wing design configuration possible, namely, a variable-geometry forward wing that sweeps forward during takeoff and landing to give stability and sweeps back 30° in level flight to reduce drag. As a bonus, the smooth structure of composite wings helps to maintain laminar air flow. Readers will get an idea of the tremendous advances made in the composites field if they would just remind themselves that until about 1975 these materials were being produced mostly on a laboratory scale. Besides the aerospace industry, chemical, electrical, automobile, and sports industries are the other big users, in one form or another, of composite materials.

This book has grown out of lectures given over a period of more than a decade to audiences comprised of senior year undergraduate and graduate students, as well as practicing engineers from industry. The idea of this book was conceived at Instituto Militar de Engenharia, Rio de Janeiro. I am grateful to my former colleagues there, in particular, J.R.C. Guimarães, W.P. Longo, J.C.M. Suarez, and A.J.P. Haiad, for their stimulating companionship. The book's major gestation period was at the University of Illinois at Urbana–Champaign, where C.A. Wert and J.M. Rigsbee helped me to complete the manuscript. The book is now seeing the light of the day at the New Mexico Institute of Mining and Technology. I would like to thank my colleagues there, in particular, O.T. Inal, P. Lessing, M.A. Meyers, A. Miller, C.J. Popp, and G.R. Purcell, for their cooperation in many ways, tangible and intangible. An immense debt of gratitude is owed to N.J. Grant of MIT, a true gentleman and scholar, for his encouragement, corrections, and suggestions as he read the manuscript. Thanks are also due to R. Signorelli, J. Cornie, and P.K. Rohatgi for reading portions of the manuscript and for their very constructive suggestions. I would be remiss in not mentioning the students who took my courses on composite materials at New Mexico Tech and gave very constructive feedback. An especial mention should be made of C.K. Chang, C.S. Lee, and N. Pehlivanturk for their relentless queries and discussions. Thanks are also due to my wife, Nivedita Chawla, and Elizabeth Fraissinet for their diligent word processing. My son, Nikhilesh Chawla, helped in the index preparation. I would like to express my gratitude to my parents, Manohar L. and Sumitra Chawla, for their ever constant encouragement and inspiration.

Socorro, New Mexico
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Krishan Kumar Chawla

About the Author

Professor Krishan Kumar Chawla received his B.S. degree from Banaras Hindu University and the M.S. and Ph.D. degrees from the University of Illinois at Urbana–Champaign, all in metallurgical engineering. He has taught and/or done research work at Instituto Militar de Engenharia, Brazil; University of Illinois at Urbana–Champaign; Northwestern University; Université Laval, Canada; and New Mexico Institute of Mining and Technology. He has published extensively in the areas of composite materials and physical and mechanical metallurgy. He is co-author of the text, *Mechanical Metallurgy: Principles & Applications*. Professor Chawla has been a member of the *International Committee on Composite Materials* since its inception in 1975.

Contents

Part I

Part II

Part III

Appendices

Part I

1. Introduction

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. Composite materials in this regard represent nothing but a giant step in the ever constant endeavor of optimization in materials.

Strictly speaking, the idea of composite materials is not a new or recent one. Nature is full of examples wherein the idea of composite materials is used. The coconut palm leaf, for example, is nothing but a cantilever using the concept of fiber reinforcement. Wood is a fibrous composite: cellulose fibers in a lignin matrix. The cellulose fibers have high tensile strength but are very flexible (i.e., low stiffness), while the lignin matrix joins the fibers and furnishes the stiffness. Bone is yet another example of a natural composite that supports the weight of various members of the body. It consists of short and soft collagen fibers embedded in a mineral matrix called apatite. A very readable description of the structure–function relationships in the plant and animal kingdoms is available in the book *Mechanical Design in Organisms* [1]. Besides these naturally occurring composites, there are many other engineering materials that are composites in a very general way and have been in use for a long time. The carbon black in rubber, Portland cement or asphalt mixed with sand, and glass fibers in resin are common examples. Thus, we see that the idea of composite materials is not that recent. Nevertheless, one can safely mark the origin of a distinct discipline of composite materials as the beginning of the 1960s. According to a 1973 estimate [2], approximately 80% of all research and development effort in composite materials has been done since 1965. This percentage must have only increased since then. Since the early 1960s, there has been an ever increasing demand for materials ever stiffer and stronger yet lighter in fields as diverse as space, aeronautics, energy, civil construction, etc. The demands made on materials for ever better overall performance are so great and diverse that no one material is able to satisfy them. This naturally led to a resurgence of the ancient concept of combining different materials in an integral–composite material to satisfy the user requirements. Such composite material systems result in a performance unattainable by the individual constituents and they offer the great advantage of a flexible design; that is one can, in principle, tailor-make the material as per specifications of an optimum design. This is a much more powerful statement than might appear at first sight. It implies that, given the most efficient design of, say, an aerospace structure, an automobile, a boat, or an electric motor, we can make a composite material that meets the bill. Schier and Juergens [3] have reviewed the

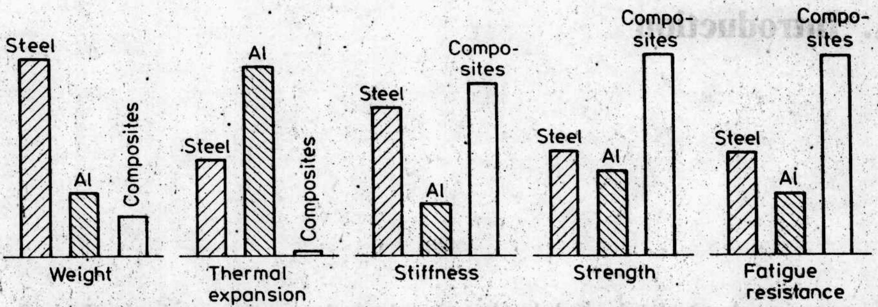

Fig. 1.1. Comparison between conventional monolithic materials and composite materials. (From Ref. 4, used with permission.)

design impact of composites on fighter aircraft. According to these authors, "composites have introduced an extraordinary fluidity to design engineering, in effect forcing the designer-analyst to create a different material for each application as he pursues savings in weight and cost." Yet another conspicuous development has been the integration of the materials science and engineering input with the manufacturing and design inputs at all levels from conception to commissioning of an item and through the inspection during the life time as well as failure analysis. More down-to-earth, however, is the fact that our society has become very energy conscious. This has led to an increasing demand for lightweight yet strong and stiff structures in all walks of life. And composite materials are increasingly providing the answers. Figure 1.1 makes a comparison, admittedly for illustrative purposes, between conventional monolithic materials such aluminum and steel and composite materials [4]. This figure indicates the possibilities of improvements that one can obtain over conventional materials by the use of composite materials. As such it describes vividly the driving force behind the large effort in the field of composite materials.

Glass fiber reinforced resins have been in use since about the first quarter of the twentieth century. Glass fiber reinforced resins are very light and strong materials, although their stiffness (modulus) is not very high, mainly because the glass fiber itself is not very stiff. The third quarter of the twentieth century saw the emergence of the so-called advanced fibers of extremely high modulus, for example, boron, carbon, silicon carbide, and alumina. These fibers have been used for reinforcement of resin, metal, and ceramic matrices. Fiber reinforced composites have been more prominent than other types of composite for the simple reason that most materials are stronger and stiffer in the fibrous form than in any other form. By the same token, it must be recognized that a fibrous form results in reinforcement mainly in fiber direction. Transverse to the fiber direction, there is little or no reinforcement. Of course, one can arrange fibers in two-dimensional or even three-dimensional arrays, but this still does not gainsay the fact that one is not getting the full reinforcement effect in directions other than the fiber axis. Thus, if a less anisotropic behavior is the objective, then perhaps laminate or sandwich composites made of, say, two different metals can be more effective. Here one has a planar reinforcement. There may also be specific nonmechanical objectives for making a fibrous composite. For example, an abrasion or corrosion resistant surface would recommend the use of a laminate (sandwich) form, while in superconductors the problem of flux-pinning requires the use of extremely fine filaments embedded in a conductive matrix. In what follows, we discuss the various aspects of composites, mostly fiber composites, in greater detail, but first let us agree on an acceptable definition of a composite material.

Practically everything is a composite material in this world. Thus, a common piece of metal is a composite (polycrystal) of many grains (or single crystals). Such a definition would make things quite unwieldy. Therefore, we must agree on an operational definition of composite material for our purposes in this text. We shall call a material that satisfies the following conditions a composite material:

1. It is manufactured (i.e., naturally occurring composites, such as wood, are excluded).
2. It consists of two or more physically and/or chemically distinct, suitably arranged or distributed phases with an interface separating them.
3. It has characteristics that are not depicted by any of the components in isolation.

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