Volume I

Composite Materials

Properties, Nondestructive Testing, and Repair

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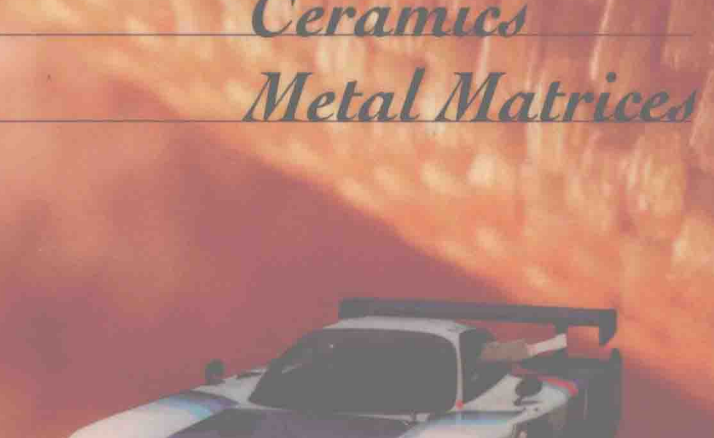
Ceramics
Metal Matrices



Mel M. Schwartz

Composite Materials, Volume I: Properties, Nondestructive Testing, and Repair

MEL M. SCHWARTZ

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The background material on the cover is a reproduction of a photograph of Kevlar, a fiber produced by DuPont which typifies raw materials used to fabricate composite parts. The Kevlar displayed here is used by Sikorsky Aircraft in the manufacturing of helicopter parts. Photograph courtesy of Sikorsky Aircraft.

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Preface

It has been recognized for many years that heterophase boundaries—interfaces between dissimilar materials—play a key role in determining the properties and performance of modern materials systems. The influence of heterophase boundaries in composites is widely recognized, and Chapter 2 discusses this matter.

The field of material technology will require scientific and industrial leadership in the next decade because this is one of several areas expected to experience unbelievable growth. To be involved in this explosion, highly specialized individuals with in-depth knowledge of materials design, process design, and product design and corporations must develop new materials and new processes to point to new pathfinder directions, routes, and roadmaps, and to stimulate thinking.

As has happened in the past, new scientific endeavors can be expected to create a demand for new and different materials. New ideas being explored include intermetallics, metal-ceramics, metal-carbons or graphites, ceramic-carbons, and plastic-ceramics. In the near future, hypersonic flight will create a need for many different and new combinations of these materials at material temperatures of 982–1482°C for up to 1 h for the trip from atmosphere to orbit and back again. High-modulus materials will also be required for parts of the structure. Other needs will require composites for liquid pressure tanks, high-conductivity structures, oxidation- and temperature-resistant ceramic matrices, diesel engines, and brake motors, as well as for a broad spectrum of uses in other industries such as electronics and computers.

It has been shown that in the modern world, advances in materials not only expand our technological capabilities but also become catalysts that drive capitalistic entrepreneurship and in turn allow society to maintain economic growth. Continuing advances in technology are absolutely critical to sustaining and improving the quality of life.

The "engineered materials age" is *now*, and we are able to put together, in some instances atom by atom, materials that are lighter, stronger, more conductive, more resilient, and smarter, and that have "memories."

Many of the materials we produce today are considered technologically mature. But the processes used to manufacture these metal, ceramic, and polymer composites are going through a revolution.

In the future smart software will design both the products and the production method. Concurrent engineering of composite materials is the technique needed to meet and keep a generation ahead of competition and stay focused on better manufacturability. This is significantly important because difficult-to-manufacture parts are universally difficult to manufacture, especially when the manufacturing processes employed have been developed for moderate to high volumes and requirements have actually fallen to low-volume levels in response to the worldwide recession or because of competitive pressures.

The early chapters of Volume I cover a general introduction to the major composite families, the fibers and matrix combinations and their properties, and how these materials have been strengthened by various mechanisms while overcoming, for example, incompatibility problems. The remaining chapters cover composite design, modeling, mechanical properties, nondestructive evaluation and repair methods, and the major uses and applications in the various industries.

Mel M. Schwartz

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1

General Introduction to Advanced Composites

1.0 INTRODUCTION

It is evident that material advances have been the key to significant technology breakthroughs throughout history. The Stone Age, the Iron Age, the Industrial Revolution, the nuclear age, the electronic revolution, the aerospace era of today—all have critically depended on, or resulted from, breakthroughs in material technology.

Today we are in the midst of a new revolution triggered by the onset of advanced composites. This radically new class of materials is characterized by the marriage of quite diverse individual components that work together to produce capabilities that far exceed those of their separate elements. Their unique properties make them the enabling materials for major technological advances. Industry representatives believe these materials will be critical to the economic trade picture well into the twenty-first century.

Typically, advanced materials have been characterized by a lengthy development cycle (20 years).[1] Today, the use of composite materials in structures of all kinds is accelerating rapidly, with the major impact already being felt in the aerospace industry where the use of composites has directly enhanced the capability of fuel-efficient aircraft in the commercial arena and new-generation aircraft in the military sphere. The increasing usage of these materials is spreading worldwide, capitalizing on developments that were the direct result of a large investment in the technology over the last two or more decades.

1.1 WHAT ARE COMPOSITES?

In their broadest form, composites are the result of embedding high-strength, high-stiffness fibers of one material in a surrounding matrix of another material. The fibers of interest for composites are generally in the form of either single fibers about the thickness of a human hair or multiple fibers twisted together in the form of a yarn or tow. When properly produced, these fibers—usually of a nonmetallic material such as carbon, silicon carbide, boron, or alumina—can have very high values of strength and stiffness. As a result of work that started in the United States in the early 1950s, there are available to us thin, continuous fibers of a variety of materials, together with the manufacturing capability to produce them on a continuous basis. In addition to continuous fibers, there are also varieties of short fibers, whiskers, platelets, and particulates intended for use in discontinuous reinforced composites.

Fiber-reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundaries) between them. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. In general, the fibers are the principal load-carrying members, whereas the surrounding matrix keeps them in the desired location and orientation, acts as a load transfer medium between them, and protects them from environmental damages due to elevated temperature or humidity, for example. Thus, even though the fibers provide reinforcement for the matrix, the latter also serves a number of useful functions in a fiber-reinforced composite material.

The principal fibers in commercial use are various types of glass and carbon, as well as Kevlar and those mentioned previously. All these fibers can be incorporated into a matrix either in continuous lengths or in discontinuous (chopped) lengths. The matrix material may be a polymer, a metal, or a ceramic. Various chemical combinations, compositions, and microstructural arrangements are possible in each matrix category.

The most common form in which fiber-reinforced composites are used in structural applications is called a laminate. Laminates are obtained by stacking a number of thin layers of fibers and matrix and consolidating them into the desired thickness. Fiber orientation in each layer, as well as the stacking sequence of various layers, can be controlled to generate a wide range of physical and mechanical properties for the composite laminate.

1.1.1 Advanced Composites

Whereas the high properties of the fibers are in part a result of their being in fiber form, as fibers they are not useful from a practical point of view. The key to taking advantage of their uniquely high properties is to embed them in a surrounding matrix of another material. The matrix acts as a support for the fibers, transports applied loads to the fibers, and is capable of being formed into useful structural shapes. The right kind of matrix can also provide ductility and toughness properties that the much more brittle fibers do not possess. The term *advanced composites* is used to differentiate those with high-performance characteristics, generally strength and stiffness, from the simpler forms like reinforced plastics.

Historically, the term advanced composites has been taken to mean "high-performance" composites. Many believe that this definition is far too restrictive and eliminates many of the applications and materials with the most potential for future growth. The development of any composite requires balancing many factors, including performance, fabrication speed, and total cost. With high-performance materials, the desire for improved properties is the dominant requirement. For many applications, however, better performance, although desirable, is not the primary need. In fact, materials may already be available with properties that meet or even exceed the performance requirements. Instead, the problem is to produce parts at sufficient speeds and low enough costs to obtain them cost-effectively. For lack of a better term, such composites can be called *cost-performance materials.*

Processing methods such as liquid molding (resin transfer molding and structural reaction injection molding), pressure molding, filament winding and tow placement, thermal forming, and pultrusion offer the most potential for reduced cost and increased speed and will be discussed in Volume II. Industry representatives believe that they must harness the chemical and physical changes that occur during fabrication to the extent that is required for the processes to be optimized and controlled. Consequently, processing science and on-line process control are key issues for the future.

1.2 COMPOSITES AND THEIR HISTORY

Modern structural composites, frequently referred to as advanced composites, are blends of two or more materials, one of which is composed of stiff, long fibers and, for polymeric composites, a resinous binder or matrix that holds the fibers in place. The fiber is strong and stiff relative to the matrix, and generally it is orthotropic; that is, it has different properties in two different directions. For advanced structural composites, the fiber is long, with a length-to-diameter ratio of over 100. The strength and stiffness of the fiber are much greater, perhaps multiples of those of the matrix material. When the fiber and the matrix are joined to form a composite, they both retain their individual identities and both influence the composite's final properties directly. The resulting composite consists of layers, or laminas, of fibers and matrix (Figure 1.1) stacked in such a way as to achieve the desired properties in one or more directions.

Modern composite materials evolved from the simplest mixtures of two or more materials to obtain a property that was not there before. The Bible mentions the combining of straw with mud to make bricks. The three key historical steps leading to modern composites were

1. The commercial availability of fiberglass filaments in 1935. This work led to the main commercial use of fiber-reinforced plastics (FRP) in the construction of aircraft radomes in the United States beginning in about 1942. Eventually, the right reinforcement and the right resin at the right price saw the production of fiber-reinforced plastic translucent sheet in 1949, followed rapidly in the early 1950s by developments in fiber-reinforced plastic boat hulls, car bodies, and truck cabs.
2. The development of strong aramid, glass, and carbon fibers in the late 1960s and early 1970s. These developments parallel the development of resins dating back to