Introduction to Composite Materials and Processes

Fibers and Reinforcements

Thermoset Resins

Cure Tooling

Ply Collation

Curing

The Interaction of Chemical Composition and Processing on Laminate Quality

Adhesive Bonding and Integrally Cocured Structure

Liquid Molding

Thermoplastic Composites

Commercial Processes

Assembly

Nondestructive Inspection and Repair

Manufacturing Processes for Advanced Composites

F. C. Campbell

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Manufacturing Processes For Advanced Composites

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Preface

This book deals is intended for anyone wishing to learn more about the materials and manufacturing processes used to fabricate and assemble advanced composites. Although advanced composites can mean many different types of fibers in either polymer, metal or ceramic matrices, this book deals with the three main fibers (glass, aramid and carbon) in polymeric matrices.

The book (Chapter 1) starts with an overview of fibers, matrices and product forms. Then, a brief introduction to the various fabrication processes is covered along with the advantages and disadvantages of composites. The first chapter wraps up with some of the applications for advanced composites. Chapter 2 examines the reinforcements and prepregging in more detail, while Chapter 3 covers the main thermosetting resin systems, including polyesters, vinyl esters, epoxies, bismaleimides, polyimides and phenolics. The principles of resin toughening are also presented along with an introduction to the physiochemical tests that are used to characterize resin and cured laminates.

Chapters 4 through 7 form a natural progression with Chapter 4 covering the basics of cure tools followed by ply collation in Chapter 5. Important ply collation methods include manual lay-up, flat ply collation, automated tape laying, filament winding and fiber placement. Vacuum bagging in preparation for cure is also discussed in Chapter 5. Chapter 6 discusses the cure process for both addition and condensation curing thermosets. The importance of both lay-up and cure variables are discussed including hydrostatic resin pressure, chemical composition, resin and prepreg, debulking and caul plates. Residual cure stresses are also covered followed by exotherm, in-process cure monitoring and cure modeling. In Chapter 7, a case study is presented on the interaction of chemical composition and processing on laminate quality.

Adhesive bonding and integrally cocured structures are introduced in Chapter 8. The basics of adhesive bonding are covered along with the advantages and disadvantages. The important of joint design, surface preparation and bonding procedures are discussed along with honeycomb bonded assemblies, foam bonded assemblies and integrally cocured assemblies.

Chapter 9 on liquid molding covers preforming technology (weaving, knitting, stitching and braiding) followed by the major liquid molding processes, namely resin transfer molding (RTM), resin film infusion (RFI) and vacuum assisted resin transfer molding (VARTM).

Thermoplastic composites are discussed in Chapter 10 including the major matrix materials and product forms. Consolidation is then covered followed by the different methods of thermoforming thermoplastics. Finally, the joining processes that are unique to thermoplastic composites are discussed.

Some of the important commercial composite processes are presented in Chapter 11 with an emphasis on lay-up, compression molding, injection molding, structural reaction injection molding and pultrusion.

Chapter 12 covers the processes that are unique to assembling composite structures. In this chapter, the emphasis is on mechanical joining including the hole preparation procedures and fasteners used for composite assembly. Sealing and painting of composite structure is also briefly discussed.

The final chapter (Chapter 13) covers two topics: nondestructive inspection and repair. NDI methods covered include visual, ultrasonics, radiographic and thermographic inspection methods. The part of repair includes fill repairs, injection repairs, bolted repairs and bonded repairs.

It should be pointed out that this book deals solely with the materials and processes used to manufacture advanced composites. It does not address the mechanics of lamina, laminates, adhesive bonding or bolted joints. If it were used as text, it would probably be more appropriate as a second course in composite materials.

The author would like to thank the following colleagues for reviewing the chapters in this book: Gary Bond, Ray Bohlmann, John Griffith, Mike Karal, Dan King, Bob Kisch, Doug McCarville, Mike Paleen and Bob Rapp. Any and all mistakes remain the responsibility of the author.

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December 2003

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Chapter 1

Introduction to Composite Materials and Processes: Unique Materials that Require Unique Processes

A composite material can be defined as a combination of two or more materials that results in better properties than when the individual components are used alone. As opposed to metal alloys, each material retains its separate chemical, physical and mechanical properties. The two constituents are normally a fiber and a matrix. Typical fibers include glass, aramid and carbon, which may be continuous or discontinuous. Matrices can be polymers, metals or ceramics. This book will deal with continuous and discontinuous fibers embedded in polymer matrices, with an emphasis on continuous-fiber high-performance structural composites. Examples of continuous reinforcements include unidirectional, woven cloth and helical winding, while discontinuous reinforcements include chopped fibers and random mat (Fig. 1).

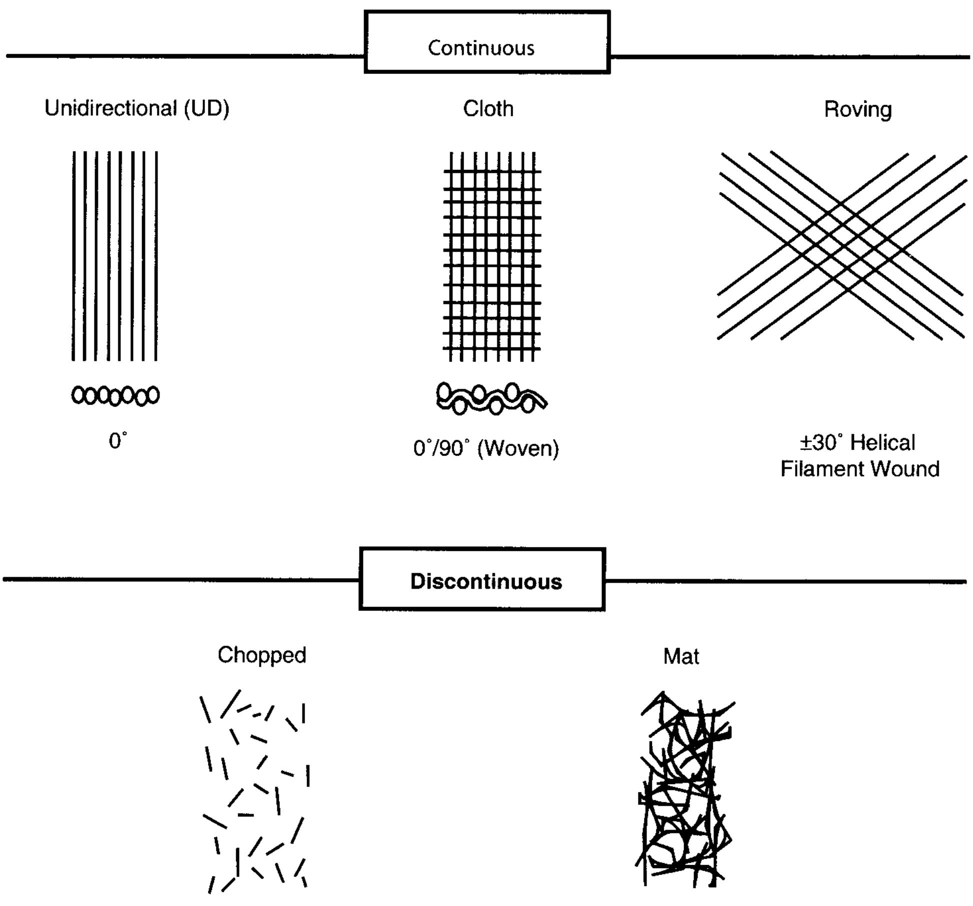

Fig. 1. Reinforcement Options

1.1 Laminates

Continuous-fiber composites are laminated materials (Fig. 2) in which the individual layers, plies or laminae are oriented in directions that enhance the strength in the primary load direction. Unidirectional (0°) laminates are extremely strong and stiff in the 0° direction; however, they are also very weak in the 90° direction because the load must be carried by the much weaker polymeric matrix. While a high-strength fiber can have a tensile strength of 500 ksi or more, a typical polymeric matrix normally has a tensile strength of only 5-10 ksi (Fig. 3). The longitudinal tension and compression loads are carried by the fibers, while the matrix distributes the loads between the fibers in tension and stabilizes and prevents the fibers from buckling in compression. The matrix is also the primary load carrier for interlaminar shear (i.e., shear between the layers) and transverse (90°) tension. The relative roles of the fiber and the matrix in determining the mechanical properties are summarized in Table 1.

Since the fiber orientation directly impacts the mechanical properties, it would seem logical to orient as many layers as possible in the main load-carrying direction. While this approach may work for some structures, it is usually necessary to balance the load-carrying capability in a number of

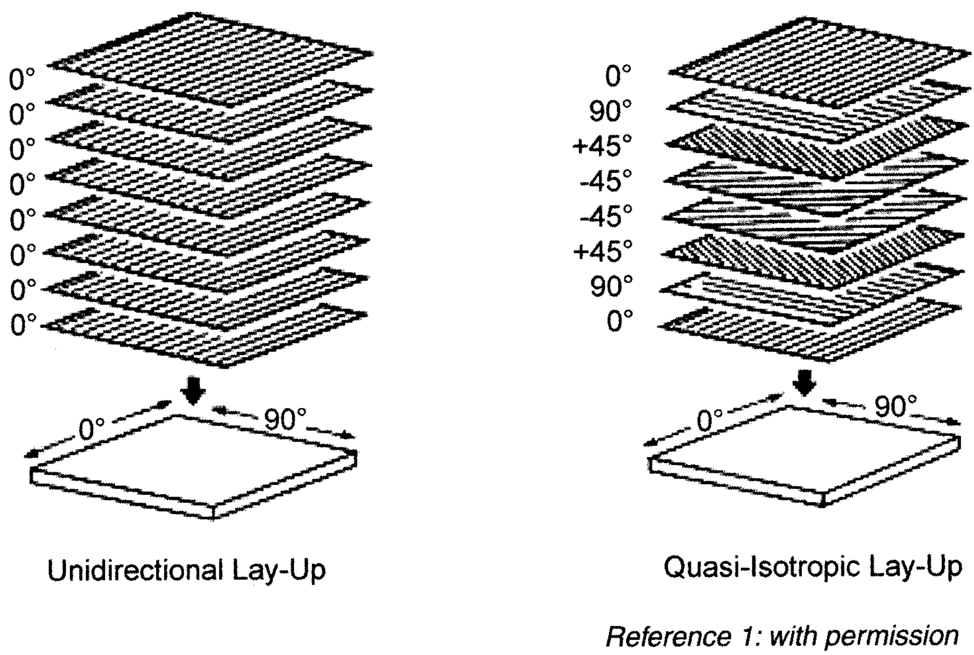

Fig. 2. Quasi-Isotropic Laminate Lay-Up

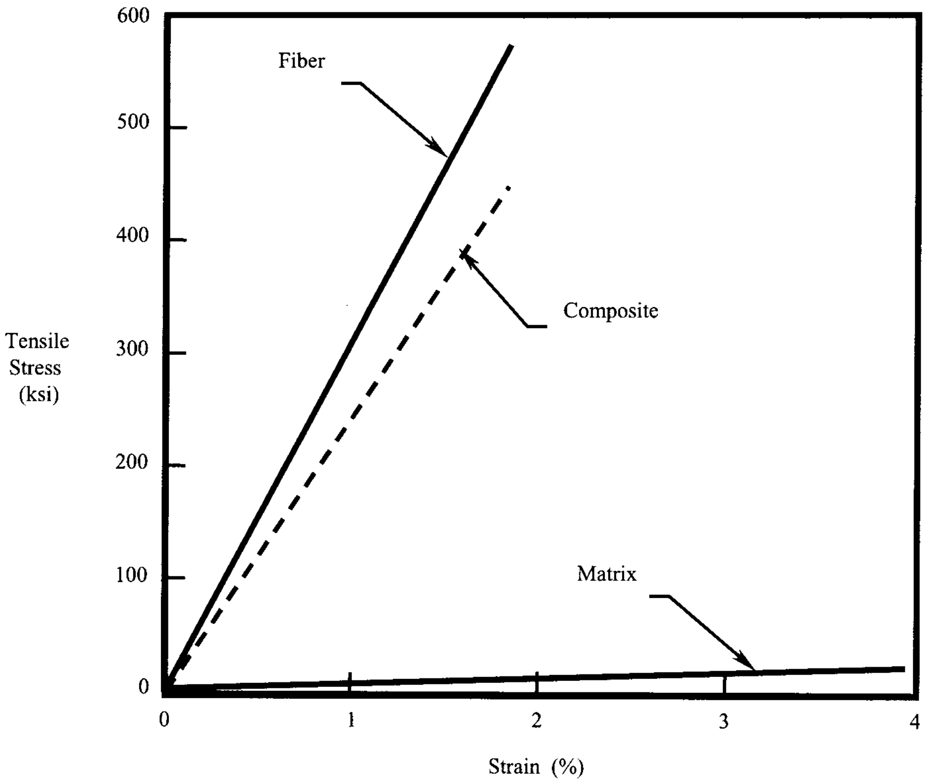

Fig. 3. Tensile Properties of Fiber, Matrix and Composite

Table 1.1 Effect of Fiber and Matrix on Mechanical Properties

Mechanical Property	*Dominating Composite Constituent*	
	Fiber	*Matrix*
Unidirectional		
0° Tension	✓	
0° Compression	✓	✓
Shear		✓
90° Tension		✓
Laminate		
Tension	✓	
Compression	✓	✓
In-Plane Shear	✓	
Interlaminar Shear		✓

different directions, such as the 0°, +45°, –45° and 90° directions. Fig. 4 shows a photomicrograph of a cross-plied continuous carbon fiber reinforcement in an epoxy resin matrix. A balanced laminate with equal numbers of plies in the 0°, +45°, –45° and 90° directions is called a quasi-isotropic laminate, since it carries equal loads in all four directions. Fig. 5 provides a graphical presentation of the preferred laminate orientations. These are preferred orientations because they are fairly balanced laminates that carry loads in multiple directions.

1.2 Fibers

The primary role of the fibers is to provide strength and stiffness. However, as a class, high-strength fibers are brittle; posses linear stress–strain

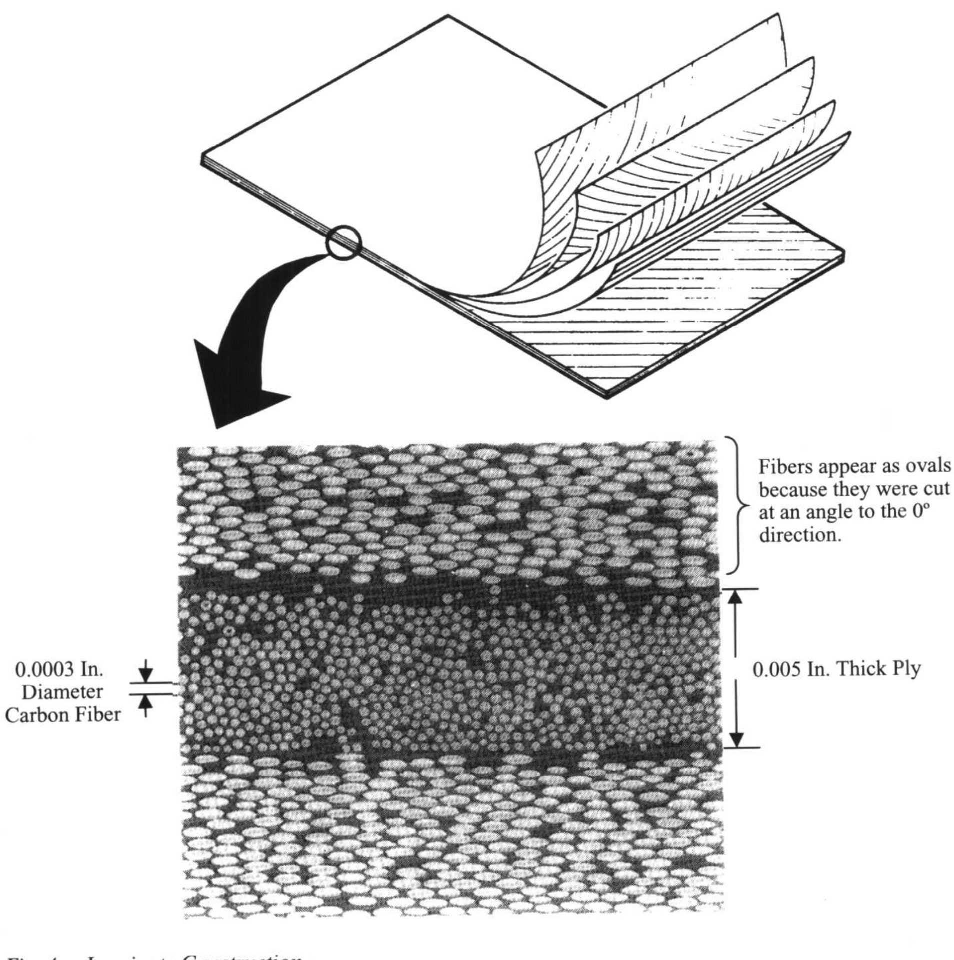

Fig. 4. Laminate Construction

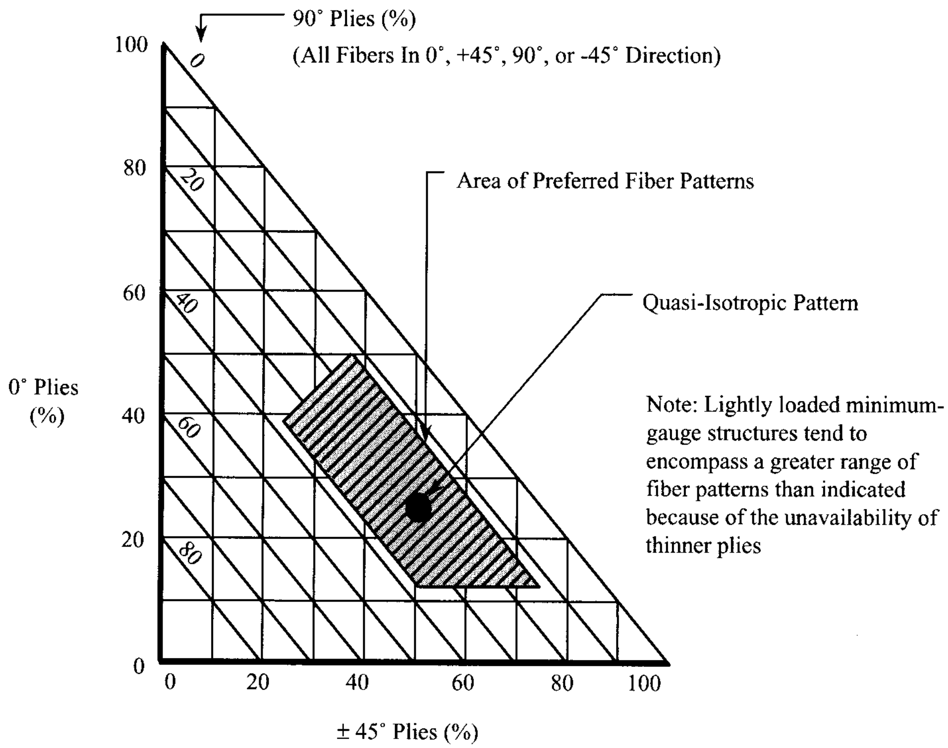

Fig. 5. Preferred Laminate Orientations

Table 1.2 Properties of Typical High Strength Fibers

Fiber	*Density lb/in^3*	*Tensile Strength (ksi)*	*Elastic Modulus (msi)*	*Strain to Failure (%)*	*Diameter (Mils)*	*Thermal Expansion Coefficient 10-6 in/in/ F*
E-glass	0.090	500	11.0	4.8	0.36	2.8
S-glass	0.092	650	12.6	5.6	0.36	1.3
Quartz	0.079	490	10.0	5.0	0.35	1.0
Aramid (Kelvar 49)	0.052	550	19.0	2.8	0.47	–1.1
Spectra 1000	0.035	450	25.0	0.7	1.00	–1.0
Carbon (AS4)	0.065	530	33.0	1.5	0.32	–0.2
Carbon (IM-7)	0.064	730	41.0	1.8	0.20	–0.2
Graphite (P-100)	0.078	350	107	0.3	0.43	–0.3
Boron	0.093	520	58.0	0.9	4.00	2.5

behavior with little or no evidence of yielding; have a low strain to failure (1-2% for carbon); and exhibit larger variations in strength than metals. Table 2 presents a summary of the major composite reinforcing fibers.