B.T. Åström

Manufacturing of Polymer Composites

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To Carol and Sara, who each in their own way made this book possible

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B. T. Åström

Department of Aeronautics
Royal Institute of Technology
Stockholm
Sweden

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PREFACE

This book has been written in the belief that a designer of structural polymer-matrix composites must have a good understanding of post-design issues to be able to create an efficient design that results in an easily manufacturable component with predictable properties. While much has been written about composite design and analysis without taking post-design issues into account, preciously little comprehensive material is available on constituent materials, manufacturing techniques, secondary processing, and other post-design issues. While there is unquestionably an immense knowledge of such issues within the composite industry, it is rare that designers possess it, which inevitably leads to designs and eventually composites with disappointing properties and unnecessarily high cost. The intention of this book is to provide a conceptual, albeit still fairly detailed, knowledge of post-design issues to enable avoidance of common design pitfalls. The book is written for engineers or individuals with similar technical background, but it is not primarily written for the worker on the shop floor. Although he (or she) may find parts of the book valuable, he is likely to find it too detailed in areas mainly of relevance to the designer. He may also find that it provides too little substance on hands-on issues, since the intention is not to provide information detailed enough for anyone to go into business manufacturing composites without investigating other sources.

The main intended audience of this book is engineering students, particularly final-year undergraduate students or graduate students. To fully appreciate the entire contents of the book, knowledge of composite design is required and it is therefore recommended that this book be studied following, or possibly concurrently with, a course on composite design. The structure of the book is such that it is best suited for sequential reading, but the contents will be considerably more meaningful if complemented by some hands-on composite manufacturing and characterization labs and factory visits to “get to smell the styrene.”

While “no one reads the introduction chapter to a textbook,” I believe that at least *Section 1.5* is important enough for careful study, since, in addition to providing a range of application examples, it discusses reasons why composites were selected over competitive materials in these cases; an understanding of the pros and cons of composites is fundamental to sensible use of the material concept. The second most important part of the book (after *Chapter 4*) is *Chapter 2*, which provides sufficient understanding of common constituents to get the gist of their processing behaviors and requirements. The treatment of polymers starts from a level that allows

mechanical engineering students with little or no recollection of past chemistry classes to follow it, meaning that the first sections may be trivial to some readers. *Chapter 3* gives quantitative substance to the qualitative treatment in *Chapter 2*. While the bulk of *Chapter 3* should be seen as a reference source, it also discusses some of the more important differences between polymer composites and conventional engineering materials. The heart of the book is *Chapter 4*, which discusses all commercially significant manufacturing techniques as well as some less common, but likely emerging, techniques. The treatment of each technique starts with a rather detailed description of the most prevalent solutions to how to make the raw material conform to the mold, followed by discussions of common raw materials and molds, as well as crosslinking and consolidation requirements. The treatment of each technique is rounded off by qualitative comparisons of technique and component characteristics, and finally application examples with reference to *Chapter 1*. *Chapter 5* treats the important issues of machining, joining, surface treatment, and repair. Of these issues, it is often only joining that is of significant relevance to the designer. A course of limited scope could end after *Chapter 4*, plus *Section 5.2* on joining, and still cover the most important post-design issues. The other parts of *Chapter 5* and the entire *Chapter 6*, which deals with quality control and characterization, often are not of primary interest to the designer, but certainly most relevant for production and quality control departments; most issues in these chapters follow as logical consequences of manufacturing. *Chapter 7* treats the not yet critical issue of composite recycling and provides an introduction to design for recycling, which already is or soon will be commonplace—at least in the automobile industry. *Chapter 8* finally deals with the important, but sometimes disheartening, aspects of the manufacturing environment, but points out that with proper knowledge, routines, and equipment, health and safety risks are minor.

While this book is primarily written as a textbook for engineering students, it will prove a good guide to post-design issues also for the practicing engineer, since a detailed subject index is included and most sections of the book can be read in isolation. For the reader desiring more detailed information than given herein, recommended sources of further reading are listed at the end of *Chapters 2–8*.

It is inevitable that this first edition contains errors and omissions and readers are therefore encouraged to point out such shortcomings to the author.

B. Tomas Åström
Sollentuna
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The computer enthusiast may be interested to know that the bulk of the book was created on a Macintosh PowerBook 540c using Microsoft Word 5.1, Claris MacDraw Pro 1.5, Aldus Photoshop 3.0, CambridgeSoft ChemDraw Pro 3.5.1, and CambridgeSoft Chem3D Pro 3.5.

NOMENCLATURE

Notation	Property	Unit
C_p	Specific heat	$\text{kJ/kg } ^\circ\text{C}$
d^p	Cell size (for honeycomb core)	m
D	Flexural rigidity of sandwich	Nm^2
E	Modulus (tensile, compressive, flexural)	Pa
G	Shear modulus	Pa
k	Coefficient of thermal conductivity (CTC)	$\text{W/m } ^\circ\text{C}$
ℓ	Length	m
r	Mandrel radius in filament winding	m
t	Thickness	m
T_g	Glass-transition temperature	$^\circ\text{C}$
T_m	Melt temperature	$^\circ\text{C}$
T_{max}	Maximum continuous-use temperature	$^\circ\text{C}$
T_{proc}	Processing temperature	$^\circ\text{C}$
v	Volume	m^3
V	Volume fraction	—
w	Weight, width	kg, m
W	Weight fraction	—
α	Coefficient of thermal expansion (CTE), angle in filament winding	$^\circ\text{C}^{-1}, ^\circ$
β	Constituent efficiency factor	—
γ	Working normal rake (in composite machining)	$^\circ$
ε	Strain (tensile, compressive, flexural)	%
η_0	Zero shear-rate viscosity	$\text{Pa}\cdot\text{s}$
ν	Poisson's ratio	—
ξ	End tab taper	$^\circ$
ρ	Density	kg/m^3
σ	Stress (tensile, compressive, flexural)	Pa
σ_{it}^*	Interlaminar shear strength	Pa
τ	Shear stress	Pa

Subscripts

b	Boss of mandrel in filament winding
c	Compressive, composite
$core$	Core
f	Fiber, flexural
$face$	Face

g	Gage
l	Longitudinal
$length$	Length (for honeycomb core)
m	Matrix
t	Transverse, tensile, tab
v	Void
$width$	Width direction (for honeycomb core)
$\perp$	Out-of-plane
	<i>Superscript</i>
$*$	Ultimate (stress or strain)

In notations with multiple subscripts, the first one refers to lamina reinforcement orientation and the second to type of testing. σ_{ll}^* thus is the longitudinal tensile strength.

ABBREVIATIONS AND ACRONYMS

3D	Three dimensions, three-dimensional
4HS	Four-harness satin (weave)
5HS	Five-harness satin (weave)
8HS	Eight-harness satin (weave)
AD	Anno Domini
AFRP	Aramid-fiber reinforced plastics
AFV	Alternative fuel vehicle
Al ₂ O ₃	Alumina
ASC	American Society of Composites
ASM	American Society for Materials
ASTM	American Society for Testing and Materials
ATR	Avions Transport Regionale
AWJ	Abrasive waterjet
BC	Before Christ
BMC	Bulk molding compound
BMI	Bismaleimide
BPO	Benzoyl peroxide
CAD	Computer-aided design
CAT	Computer-aided tomography
CEN	Comité Européen de Normalisation, European Committee for Standardization
CEU	Commission of the European Union
CFC	Chlorofluorocarbon
CFM	Continuous filament mat
CFRP	Carbon-fiber reinforced plastics
CMC	Ceramic-matrix composite
CNG	Compressed natural gas
CNS	Central nervous system
CO ₂	Carbon dioxide
CSM	Chopped strand mat
CT	Computed tomography
CTC	Coefficient of thermal conductivity
CTE	Coefficient of thermal expansion
CVD	Chemical vapor deposition
DBP	Double-belt press
DETA	Diethylenetriamine

DFA	Design for assembly
DFD	Design for disassembly
DFR	Design for recycling
DGEBA	Diglycidylether of bisphenol A
DGEBPA	Diglycidylether of bisphenol A
DIN	Deutsches Institut für Normung, German Institute for Standardization
DMC	Dough molding compound
DSC	Differential scanning calorimetry
ECM	Electro-chemical machining
EDM	Electro-discharge machining
EN	European norm (standard)
EP	Epoxy
EPA	United States Environmental Protection Agency
ESPI	Electronic speckle pattern interferometry
EV	Electric vehicle
FE	Finite element
FRP	Fiber reinforced polyester (or plastic)
GFRP	Glass-fiber reinforced plastics
GMT	Glass-mat reinforced thermoplastic
GPRMC	Groupeement Européen des Plastiques Renforcés/Materiaux Composites, Organisation of Reinforced Plastics/Composite Materials
HAZ	Heat-affected zone
HDT	Heat deflection temperature
HM	High modulus
HS	High strength
HS/S	High strength/strain
HSRTM	High-speed resin transfer molding
HSS	High-speed steel
IARC	International Agency for Research on Cancer
ILSS	Interlaminar shear strength
IM	Intermediate modulus
IMC	In-mold coating
IR	Infrared
ISO	International Organization for Standardization
LCA	Life-cycle assessment
LCP	Liquid crystalline polymer
LSE	Low styrene emission
MCMV	Mine counter-measure vessel
MDI	Methylene diphenyl diisocyanate
MEK	Methyl ethyl ketone
MEKP	Methyl ethyl ketone peroxide
MIBK	Methyl isobutyl ketone

MMC	Metal-matrix composite
MSDS	Material safety data sheet
MSW	Municipal solid waste
NDE	Nondestructive evaluation
NDI	Nondestructive inspection
NDT	Nondestructive testing
OCF	Owens-Corning Fiberglas
OEL	Occupational exposure level
PA 12	Polyamide 12
PA 6	Polyamide 6
PA 6,6	Polyamide 6,6
PAI	Poly(amide imide)
PAN	Polyacrylonitrile
PAS	Poly(aryl sulfone)
PBT	Poly(butylene terephthalate)
PC	Polycarbonate
PCD	Polycrystalline diamond
PE	Polyethylene
PEEK	Poly(ether ether ketone)
PEI	Poly(ether imide)
PEK	Poly(ether ketone)
PEKK	Poly(ether ketone ketone)
PEL	Permissible exposure level
PEL-C	Ceiling PEL
PES	Poly(ether sulfone)
PET	Poly(ethylene terephthalate)
PI	Polyimide
PMI	Polymethacrylimide
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PPE	Personal protective equipment
PPS	Poly(phenylene sulfide)
PS	Polystyrene
PSU	Polysulfone
PUR	Polyurethane
PVC	Polyvinylchloride
QA	Quality assurance
QC	Quality control
RIM	Reaction injection molding
RRIM	Reinforced reaction injection molding
RT	Room temperature
RTM	Resin transfer molding
SACMA	Suppliers of Advanced Composite Materials Association
SAMPE	Society for the Advancement of Material and Process

	Engineering
SCRIMP	Seeman composites resin infusion molding process
SES	Surface-effect ship
SiC	Silicon carbide
SiO ₂	Silica
SMC	Sheet molding compound
SMC-C	Sheet molding compound with continuous and aligned reinforcement
SMC-C/R	Sheet molding compound with a blend of random and continuous, aligned reinforcement
SMC-R	Sheet molding compound with random reinforcement
SPE	Society of Plastics Engineers
SPI	Society of the Plastics Institute
SRIM	Structural reaction injection molding
SRM	SACMA recommended method
STEL	Short-term exposure limit
TDI	Toluene diisocyanate
T_g	Glass-transition temperature
T_m	Crystalline melting temperature
T_{max}	Maximum continuous-use temperature
T_{proc}	Processing temperature
TWA	Time-weighted average
UD	Unidirectional
UHM	Ultra-high modulus
UP	Unsaturated polyester
UV	Ultraviolet
VARI	Vacuum assisted resin injection/infusion
VE	Vinylester
ZEV	Zero-emission vehicle

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CHAPTER 1

INTRODUCTION

Composite materials are the most advanced and adaptable engineering materials known to man. While composite materials in the sense used in this book—a conscious combination of two or more distinct material phases into one engineering material where the phases are still discernible—are only about five decades old, it is instructive to consider the evolution of materials and composites in a historical perspective. In school we were probably all taught that (past) civilizations are characterized by the most advanced engineering materials used at the time, e.g. stone, bronze, and iron ages, to indicate the fundamental importance of the state of engineering materials to mankind. It has always been—and to a significant degree still is—the properties of engineering materials that set the limits to man’s engineering achievements; the more capable the materials, the greater the scope for groundbreaking engineering achievements.

1.1 The Evolution of Materials

During the stone age flint, which is a ceramic, was the best cutting material known to man. Metals were of little importance, whereas natural polymers, composites, and ceramics dominated in engineering applications (houses, weapons, boats, etc.), see *Figure 1-1*. From then on, development of metal-working skills strongly dominated most engineering achievements well into the 20th century. In particular the position of steel has been remarkable since the middle of the 19th century. However, in the 1960s things started to change and the development in engineering materials is no longer dominated by steel and other metals, which are in relative decline worldwide. Instead polymers, composites, and ceramics are regaining their relative importance to man. The difference is that while natural polymers, composites, and ceramics dominated in the past, the current developments are due to man-made, or synthetic, materials. While these new materials, which are being developed rapidly, open up exciting and sometimes mind-boggling

new opportunities, they also require new methods and capabilities in design and manufacturing [1].

Figure 1-1 Schematic of the evolution of materials used in mechanical and civil engineering applications and their relative importance to mankind. PE, PMMA, PC, PS, and PP are synthetic polymers; most of them are introduced in *Chapter 2*. GFRP, CFRP, and AFRP are abbreviations for glass-, carbon-, and aramid-fiber reinforced plastics, or composites, which are the subject of this book. Note that the relative importance is not in terms of tonnage or value and that the time scale is nonlinear. Redrawn from reference [1]

The preceding discussion and figure allude to naturally occurring polymers and ceramics, but there are also numerous examples of natural composites, including wood, bone, insect exoskeleton, mollusk shell, and countless others (although *Figure 1-1* places wood, and probably would have placed all other natural composites, in the polymer category; it is a matter of definition). Natural composites tend to be weaker and less stiff than synthetic composites, but are often superior in terms of design and manufacture. Natural composites are also “smart materials” in that they adapt to the environment. As an example, a tree grows in such a way that it becomes stronger in the direction where strength is required and any incurred damage is gradually repaired. The composite concept is obviously not an invention.

As far as conscious human use of the composite concept goes, the earliest known example is the early Egyptians, who used straw to reinforce clay from the Nile to make brick. (There is even a biblical reference to this practice: Exodus 5:7.) In the third millennium BC, the Egyptians also made papyrus “paper” from the papyrus reed by placing strands of the reed parallel to each other to form layers, which then were stacked perpendicular to

each other in alternate directions; the stack was then allowed to dry under pressure to form the paper-like sheet. Also the Chinese used straw-reinforced brick and in 108 AD invented paper (the word paper is, incidentally, derived from the word papyrus), which is a random, planar arrangement of individual cellulose fibers held together by a binder. Although predominantly known as Chinese and Japanese art forms, the invention of metal-wire reinforcing of ceramics has also been attributed to the Egyptians [2].

In the preceding paragraphs the noun composite (which is derived from the Latin verb *componere*, meaning to put together) has been used in a very generous sense. Moreover, in contemporary language, composite is used in several other contexts than that of this book. The meaning used herein is well established in engineering terminology and refers to a combination of two or more distinct materials into one with the intent of suppressing undesirable properties of the constituent materials in favor of the desirable properties. This definition obviously does not include metal alloys or polymer blends, which are material combinations on the atomic level. The key feature of a composite is that it offers a combination of properties that are not available in any isotropic material; composites are an entirely new and unique material family.

1.2 The Composite Concept

In load-bearing, or structural, applications, composites in most cases comprise a bulk phase enclosing a fibrous reinforcing phase; in conventional terminology one talks of matrix and reinforcement. The objective of the matrix is to integrally bind the reinforcement together so as to effectively introduce external loads to the reinforcement and to protect it from adverse environmental effects. While the matrix gives a composite its shape, surface appearance, environmental tolerance (to high temperature, water, ultra-violet light, etc.), and overall durability, it is the fibrous reinforcement that carries most of the structural loads and thus largely dictates macroscopic stiffness and strength.

Although numerous examples of the composite concept may be distinguished in everyday life, including paper, Kraft paper, particle (chip) board, and reinforced concrete to mention just a few, the most specialized incarnations are those that are the main subject of this book. Practically all successful structural composites have man-made constituents. The matrix may be metallic, ceramic, or polymeric in origin. While metal and to some degree ceramic matrices are used in structural composite applications, polymer matrices are currently by far the most significant matrix category and this book therefore concentrates on polymer composites. There are two main polymer families; thermosets and thermoplastics. The vast majority of current composite applications utilize thermosets, which solidify through a chemical reaction called crosslinking or cure. Thermoplastics differ in that

they can be melted and therefore solidify through cooling of the melt without any chemical reaction taking place. In polymer-matrix composites, the common reinforcement types are (in order of decreasing importance) glass, carbon, and polymer. The composite reinforcement may be discontinuous ("short fibers") or continuous ("endless fibers") and randomly oriented or aligned, see *Figure 1-2*.

Figure 1-2 Schematic of different reinforcement configurations

Since the reinforcement is the primary load-bearing constituent, its configuration (form and degree of orientation in the matrix) is critical to the macroscopic properties of the composite. It should therefore come as no surprise that the most impressive mechanical properties are found in composites with continuous and aligned reinforcement, see *Figure 1-3*. While clearly structurally inferior, composites with randomly oriented reinforcement are common in both structural and semi-structural applications; whether the reinforcement in such composites is discontinuous or continuous is of secondary importance from a structural point of view. In many applications, different reinforcement configurations are mixed within one and the same component.

Probably the most common reason why polymer composites are used in structural applications is that they offer a given property, often stiffness, at a lower weight than the competition, which most of the time is a metal, but sometimes also plastic, wood, or concrete. One therefore talks of excellent *specific* stiffness and strength, i.e. property normalized with (divided by) density. There are numerous potential advantages of composites other than their excellent structural capabilities, including corrosion resistance, electrical insulation, reductions in tooling and assembly costs, and many more.

Figure 1-3 Fracture surface of continuous carbon-fiber reinforced epoxy composite. The fiber diameter is 7 μm . Photograph courtesy of Jakob Kutteneuler, Department of Aeronautics, Royal Institute of Technology, Sweden

These advantages, illustrated with a number of application examples, are further discussed in *Section 1.5*. It is, however, important to realize that these potential advantages assume that appropriate constituents are chosen, since if *inappropriate* constituents are chosen, the result instead may be that the composite alternative turns out to be vastly inferior.

While it is easy to become impressed with the potential advantages of composites, the disadvantages must not be ignored. It is probably essentially true that if one disregards cost, a polymer composite can outperform any other engineering material in all respects except temperature tolerance. It is nevertheless rare that cost is not important, thus one also has to take into account less desirable traits of composites, such as high raw material cost, lack of knowledge and experience, and difficult manufacturing. Composites are therefore certainly not appropriate in all applications; a critical assessment of the material alternatives must always be made in terms of performance-to-cost ratio. It is highly unlikely that decreases in raw material cost due to increasing production volumes alone will make composites directly cost-competitive with other materials in any wide range of applications, but in terms of knowledge, experience, and manufacturing matters can be significantly improved to further enhance the competitiveness of composites.

1.3 Design and Manufacturing

Almost all designers have been educated on and still only work with materials that are essentially isotropic, e.g. metals, and only the odd one has any real knowledge and experience of composites, which quickly make the design task vastly more difficult due to the inherent anisotropy of the material. There are centuries' worth of compiled experience and material data on conventional construction materials to be found in the literature. In contrast, there is at best decades' worth of experience to draw upon for composites and openly available material data bases are fragmented and incomplete. So why abandon known materials that are comparatively easy to design with? The answer is that the potential rewards in product performance, and thus ultimately cost, are vast. However, while composites potentially offer numerous advantages, they require a lot from the designer. Since few designers and other individuals who specify materials feel comfortable with composites, it is unlikely that these will see widespread acceptance until the gospel is spread to a wider audience. In short the answer is education, both at university level and as continuing education of practicing engineers. While countless universities worldwide educate engineers to be capable of designing with conventional materials, only a handful provide any composite-related education worth the name. Although composite design has been a field of active research for a couple of decades and some good textbooks and design guides are available, there has been remarkably little impact in terms of the number of applications. The exceptions are the aerospace and boat-building industries, where composites are well established since they offer clear advantages over conventional materials.

With composites manufacturing is more critical than with conventional construction materials, since material and component are normally manufactured simultaneously. The simultaneous manufacture of material and component adds to the burden of the designer, since he* must also have an understanding of how the component he is designing should be manufactured. While composites offer design opportunities unbeknown to metal design (e.g. far-ranging parts integration and geometrical complexity), there are also numerous restrictions to keep in mind (e.g. sharp corners and significant thickness differences). There is not only the issue of what is technically manufacturable, but also what can be economically manufactured; all aspects of manufacturability are strongly dependent on manufacturing technique and material. As if this were not enough, the properties of the component are strongly dependent on how it was manufactured, both through which technique and under what conditions. There is consequently a strong need for the composite designer to have an

* While male pronouns (instead of both male and female) are used throughout this book in the name of readability, this is not intended as an affront to female readers, who are encouraged to make the field of composites less male-dominated.

understanding of both materials and manufacturing. While a university student may find the odd course on composite design, chances are that he will learn little or nothing on manufacturing techniques and processing requirements of raw materials. In fact, he may look into the curricula of universities worldwide and still find extremely few opportunities to learn about composite manufacturing.

Design difficulties apart, several of the other disadvantages of composites one way or another also have their origin in manufacturing. Most proven manufacturing techniques are labor-intensive and thus costly. Partly due to the extent of manual labor, partly due to variations in raw material quality, and partly due to the aforementioned property dependency on processing conditions, repeatability may be poor, leading to a high scrap ratio or expensive post-manufacturing repair to further add to final component cost. Although some manufacturing techniques are certainly well established and reasonably well understood, it is probably fair to say that composite processing science is far from completely investigated. Over the past decade, significant research and development efforts have resulted in many enlightening investigations that have created a more fundamental understanding of important mechanisms in composite manufacturing, but countless unsolved issues remain.

It is the aforementioned shortcomings in composite-related education, the apparent lack of comprehensive textbooks on manufacturing-related topics, and the many unresolved issues in composite processing science that are the ultimate reasons why this book has been written.

1.4 Market

Just as with most new materials (cf. *Figure 1-1*), the development of high-performance polymer composites, often called advanced composites, has been driven by military, and later aerospace, needs, where performance often is more important than cost. While the search for new and improved materials is likely to continue to be driven by military needs and desires, most types of polymer composites have now become commodity materials. This transition from specialized “high-tech” to commodity material concept does not mean that improvements in material performance will cease, but the emphasis of the development has shifted to improvements in design, manufacturability, and ultimately cost.

While the main developmental efforts in the field of advanced composites have been military in origin, a largely parallel development of “low-tech” composites has taken place in for example the electrical and boat-building industries. In electrical applications, the interest was spurred by a need for a nonconductive engineering material, whereas composite boats early on were found to have advantages in terms of manufacturing cost, durability, and reduced need for maintenance.

That composites have become commodity materials in many areas becomes obvious when studying statistics on composite shipments in terms of weight, see *Figures 1-4* and *1-5*. Both in Europe* and in the United States transportation is the major applications area, followed by construction. The figures further illustrate the importance of consumer products, including sporting goods, and applications where electrical insulation and corrosion-resistance are valued. The figures also illustrate the apparent lack of significance of aerospace and defense. However, the data of the figures refer to weight and if value instead were to be considered, aerospace and defense would certainly become significant, since these industries tend to use very expensive materials and manufacturing techniques. Studying *Figures 1-4* and *1-5* it is apparent that direct comparisons between Europe and the United States are difficult since categorizations differ significantly.

Figure 1-4 Market share of composite shipments in Europe in 1996 (by weight). Application examples of the respective categories include Transportation: all road, rail, water, and air applications, except industrial and agricultural equipment; Construction: general construction, civil engineering, kitchen, and bathroom interiors; Industrial/agricultural equipment: tanks, vats, silos, pipes; Electrical/electronic: circuit boards, equipment housings, insulating materials; Consumer products: furniture and electric household appliances; Sport/leisure: skis, boats, pools. Data from reference [3]

Having considered the relative distribution between application areas, it is instructive to consider the overall historical development of composite shipments (and some predictions). *Figures 1-6* and *1-7* illustrate that composite shipments have been increasing at a rather healthy pace in both Europe and the United States; the developments are in fact rather similar. In 1996 the overall composite shipments were approximately equal in Europe

* For the purpose of the statistics presented here, "Europe" is synonymous with the 15 nations of the European Union as well as Norway and Switzerland.

Figure 1-5 Market share of composite shipments in the United States in 1996 (by weight). Application examples of the respective categories include Transportation: road and rail applications; Consumer products: sporting goods and garden equipment; Appliance/business equipment: electric household appliances; Other: medical applications; other categories largely coincide with those of *Figure 1-4*. Data from reference [4]

Figure 1-6 Market development for composite shipments in Europe 1986–1999 (by weight). Shaded line indicates predictions. Data, which have been normalized with respect to 1986, from reference [3]

and the United States at 1.5 million tons [3,4]. It is noteworthy that composite shipments appear to follow the general economic trends; the data of the figures clearly indicate downturns approximately coincident with the recession in the beginning of the 1990s. Figure 1-7 illustrates that in the United States transportation and electrical applications are ever more dominating at the expense of aerospace, defense, and marine applications.

Figure 1-7 Market development of composite shipments in the United States 1986–1996 (by weight). For clarity, the shaded region denotes the maximum spread of construction, corrosion-resistant equipment, other, consumer products, and appliance/business equipment. Data, which have been normalized with respect to 1986, from reference [4]

Figure 1-8 Breakdown of composite shipments in Europe in 1996 by country/region (by weight). Data from reference [3]

Taking a closer look at Europe, the dominance of the German-speaking parts is clear, followed by Italy, and France, see *Figure 1-8*. While composite shipments to parts of Europe other than those included in the figure are not insignificant, they are nevertheless not included in these statistics.

1.5 Application Examples

This section attempts to provide both representative and exceptional composite application examples and discusses the likely reasons why polymer composites were chosen instead of competitive materials. *Table 1-1* lists some of the many potential advantages of composites over more conventional engineering materials.

The intent of this section is to give the reader a feeling for the scope of possibilities of composites, but also to provide a common compilation of applications that subsequent chapters may refer to. This section therefore inevitably introduces terminology and refers to material systems and manufacturing techniques that have not yet been defined. For the purposes of the treatment in this chapter, these references can be ignored until they are defined in subsequent chapters.

1.5.1 Transportation Applications

From *Figures 1-4* and *1-5* it is apparent that transportation is the dominant application sector for composites and, according to *Figure 1-6*, the fastest growing one (at least in the United States, but probably in most areas of the world). In this section, “transportation” is taken to include all road and rail applications, whereas marine and aerospace applications have been awarded their own sections below.

The predominant reason for use of composites in transportation applications perhaps ought to be the high specific stiffness and strength obtainable, so as to manufacture a lighter vehicle that therefore can be equipped with weaker drivetrain, suspension, etc., to become even lighter; this is a so-called positive weight spiral. Such weight savings can be exploited to reduce fuel consumption or to increase payload (mainly for commercially used vehicles). The specific-stiffness advantage is indeed exploited where large weight reductions are valued, but mostly in somewhat unconventional applications. Such applications include Formula One and motorcycle racing, where no effort is spared to save weight and thus gain performance. In Formula One cars basically all parts that can be polymer composites are and the body is a self-supporting aircraft-like structure employing aerospace materials, design methodologies, and manufacturing techniques. Another transportation area where composites are slowly being applied to save weight is trains. High-speed trains in Europe and Japan particularly, but also freight and commuter trains contain increasing amounts of composites. There is even an example of entire railway cars being filament wound (see *Section 4.2.5*) as square tubes.

Table 1-1 Potential advantages of composites

<i>Potential advantage</i>	<i>Typical applications or application areas</i>
Specific strength and stiffness	All applications, but particularly in aerospace, defense, sporting goods, industrial machinery, bridges
Fatigue properties	Aircraft, fan blades, pressure vessels, drive shafts
Damping properties	Drive shafts, sporting goods, musical instruments
Corrosive resistance/ low maintenance requirements	Industry, marine, off-shore, bridges
Thermal insulation	Refrigerated containers, building panels, fire walls and doors
Electrical insulation	Electrical housings, transformer spacers, cable trays, ladders
Radar transparency	Aircraft radomes, patient supports for X-ray equipment
Nonmagnetic	Mine sweepers, patient supports for magnetic resonance scanners
Biological inertness	Replacement joints, tendons
Energy absorption	Helmets, bulletproof partitions, armor, crash barriers
Fire and smoke properties	Fire walls and doors, aircraft interiors
Geometrical complexity/ parts integration	All applications, but particularly in automobiles and aircraft
Anisotropy	Aircraft, springs, pressure vessels, piping
Shape flexibility	Used to achieve shapes that cannot (at similar cost) be made with metals, for example in automobile body panels
Thermal expansion/ dimensional stability	Used to eliminate thermal expansion, for example in satellite antennae
Tooling cost	All applications, but particularly in automobiles and aircraft
Manufacturing cost	All applications, but particularly in automobiles and aircraft
Low scrap value	Used to eliminate theft, for example of reusable beer kegs and road signs (where steel/aluminum designs are stolen)
"High-tech" image	Sporting goods, automobiles

However, in most parts of the world fuel still does not cost enough for anyone to be prepared to pay a higher up-front cost for their new car in order to reduce operating costs over a number of years, although the trend is certainly slowly changing towards lighter vehicles. While many car components indeed do tend to get lighter, there is a counteractive trend in that we expect cars with increased performance and more and more electronic gadgets, so the potential net weight loss is largely lost along the way.

One emerging motivation to produce lightweight vehicles is the alternative fuel vehicle (AFV), which runs on non-petroleum energy forms. Naturally, the ideal solution would be a zero-emission vehicle (ZEV), which with current technology essentially is synonymous with an electric vehicle (EV). Due to the unimpressive capacity of available battery types, EVs end up slow, have poor range, and are terribly expensive when compared to conventional automobiles. EVs also may take hours to recharge. Although battery technology is constantly improving it appears that no commercially viable breakthrough in battery technology to solve this technical inferiority is imminent. For the time being, greater improvements in performance may be obtained through reduction in vehicle weight and most reasonably successful EVs consequently rely heavily on composites.

Much work is underway worldwide to produce EVs with acceptable performance at a reasonable cost. In the United States the work is perhaps the most urgent, since in 1990 the California Air Resources Board decided that by 1998, 2 percent of the vehicles sold in the state by the seven companies with the largest market share would have to be ZEVs; by 2003, the figure should be 10 percent. At the time of writing, late 1996, the board has withdrawn its 1998 requirement after recognizing that it would have been impossible to meet, but still stands by the 2003 figure.

While specific stiffness and strength are rarely valued by the automobile industry (nor its customers), there is still the most convincing argument of them all for use of composites—reduction in production cost. A set of molds for sheet metal stamping is extremely expensive and such an investment only pays off if production series are long. For vehicles manufactured in short series, such as sports cars and new models for which the sales potential is not known, such investments may be prohibitively large. If composites are used instead of sheet metal, mold costs are much lower since fewer molds are required (sheet metal stamping is incremental, thus requiring several sets of molds, while compression molding of composites (see *Sections 4.2.4 and 4.3.3*) requires one set only). Molds for composites may also be much less rigid, since pressures in many manufacturing techniques are much lower than in sheet metal stamping. In fact, for short series it is quite feasible to use molds that themselves are polymer composites.

Another major cost saver, which is valid for any length series, is to employ the possibility of extensive geometrical complexity to integrate what in steel would be several smaller parts into one composite component;

far-ranging parts integration may lead to significantly reduced assembly costs. Cost reduction without doubt is the most persuasive argument, but the aforementioned possibility of geometrical complexity also may be used to manufacture, for example, body panels that cannot (at least at a reasonable cost) be made from sheet metal, thus allowing a greater design freedom and potentially more appealing vehicle aesthetics.

There are by now numerous examples of the use of composites in automotive applications, but the best known is probably still the venerable Chevrolet Corvette. The Corvette has had composite body panels since its introduction in 1953 and continues to be General Motors' testbed for composites, where novel composite applications are tried before being introduced in other models. While there are ample examples worldwide of the design freedom and parts integration that composites offer, examples of composite body panels fastened to a conventional steel space frame include several Lotus cars, the now no longer manufactured BMW Z1 and Pontiac Fiero (see *Figure 1-9*), the Dodge Viper (see *Figure 1-10*), and the Renault Espace (see *Figure 1-11*).

Figure 1-9 The Pontiac Fiero GT with composite body panels, some manufactured using reinforced reaction injection molding (see *Section 4.2.3.5*)

Whether a composite solution is chosen or not strongly depends on series length, partly due to the previously mentioned differences in mold costs and partly due to the fact that composite manufacturing in most cases is more time-consuming than sheet metal stamping. On the other hand, the marginal cost of manufacturing a composite component is often higher than the metal counterpart, so if a newly introduced vehicle becomes a commercial success and sales increase, sheet metal stamping may gradually become a financially sounder solution than composites. As series grow longer a short

Figure 1-10 The majority of the glass-reinforced body panels of the Dodge Viper RT/10, with an 8-liter V10 engine providing 400 hp, are manufactured through resin transfer molding (see Section 4.2.3.2). Photograph courtesy of Harry Karlsson Bil, Partille, Sweden

Figure 1-11 All body panels of the new Renault Espace (except for the hood, which is sheet steel) are compression molded from glass-reinforced unsaturated polyester sheet molding compound (see Section 4.2.4). Photograph courtesy of Renault Presse

cycle time also becomes more important. These may very well be the reasons why the body panels of the General Motors minivans (conceptually akin to the Renault Espace in *Figure 1-11*), which originally were composites, now are manufactured from steel.

Series length similarly determines which composite manufacturing technique is the most economical. The Renault Espace originally had composite body panels that were resin transfer molded (see *Section 4.2.3.2*), but as sales have picked up compression molding (see *Section 4.2.4*), which is less labor-intensive and more rapid, has become a more sensible manufacturing route. For really short production series, a significant degree of manual labor may make sense; the body panels of the Dodge Viper are resin transfer molded, which requires a moderate degree of manual involvement, while the body panels of the Lotus Elise are hand laidup (see *Section 4.2.1.1*), which requires even more manual labor.

Composites are also used in some truck and bus applications, usually in the form of body panels (see *Figure 1-12*). Other applications include a dashboard (see *Figure 1-13*), and even complete buses (see *Figure 1-14*).

Figure 1-12 Body panels on heavy vehicles that see considerable wind loads are often composites. For example the spoiler at the top, part of the grille, and the forward corner panels of the driver's cab of this Scania truck are compression molded from a glass-reinforced unsaturated polyester sheet molding compound (see *Section 4.2.4*). Most other body panels, as well as dashboard and several other interior structures, are unreinforced thermoplastics. Photograph courtesy of Scania Sverige, Södertälje, Sweden

Figure 1-13 Dashboard of a heavy Volvo truck compression molded from glass-reinforced polypropylene (see *Section 4.3.3.1*); the molded and painted component is shown at the top and the complete dashboard below it. Photographs courtesy of Volvo Truck Corporation, Göteborg, Sweden

Although not yet very common, composites are also used in truly structural vehicle applications. The previously discussed Formula One body is self-supporting and some rare sports cars have also eliminated the traditional metal frame. Most major automobile manufacturers have also one way or another evaluated the concept of using a self-supporting composite base plate in conventional automobiles, but so far this concept has not been made commercial. Self-supporting composite bodies are, however, used in some buses (see *Figure 1-14*), truck trailers, and specialty vehicles (see *Figure 1-15*). Structural components in vehicle applications include wheels, battery trays, drive shafts, pressure vessels for compressed natural gas (CNG), leaf springs, flywheels (for energy storage on AFVs), and front ends (see *Figure 1-16*), to mention but a few. In many of these cases it is the reduction in the number of parts and thus the assembly that is the reasons for use of composites. For example, the one-piece composite front end shown in *Figure 1-16* would have required eleven steel parts, while a one-piece composite drive shaft for a light truck may replace a two-piece steel construction with a joint. Composites also turn up in an increasing number of non-structural or semi-structural under-the-hood applications, where temperatures are on

Figure 1-14 Neoplan bus with self-supporting sandwich* body of glass- and carbon-reinforced unsaturated polyester on expanded polymer foam core. This bus weighs a third less than any comparable bus and offers a load capacity slightly larger than its empty weight. Photograph courtesy of Gottlob Auwärter, Stuttgart, Germany

Figure 1-15 All-terrain vehicle with self-supporting sandwich body. The sandwich panels, which have polyvinyl chloride and polyurethane foam cores and glass-reinforced unsaturated polyester faces, are manufactured through resin transfer molding (see Section 4.2.3.2). The six panels that make up each unit are adhesively joined using an epoxy adhesive. Photograph courtesy of Hägglunds Vehicle, Örnsköldsvik, Sweden

* In composite terminology, a sandwich is a structure where a relatively weak and light material, such as a polymer foam or honeycomb material, is interleaved between and integrally bonded to two stiff sheets of material, most often composite laminates. One talks of a core being sandwiched between two faces. The purpose of using a sandwich structure is generally to obtain high flexural rigidity; the sandwich concept is further discussed in Section 2.4.

Figure 1-16 One-piece front end of the Volvo 850 compression molded from glass-reinforced polypropylene (see *Section 4.3.3.1*). In this case, the alternative steel solution would have comprised eleven stamped components spot-welded into one structure. Substantial reductions in molding and assembly costs were the deciding factors in favor of the composite alternative, although the weight was also lowered by 40 percent. Photograph courtesy of Volvo Car Corporation, Olofström, Sweden

the order of 150°C and sometimes higher. New materials and manufacturing improvements enable applications such as noise shields, heat shields, engine top covers, oil sumps, and air intake manifolds, although experimental engines have been made almost entirely from composites.

1.5.2 Marine Applications

The fiberglass, or glassfiber, boat was the first large-scale application of composites and the marine industry is still one of the major consumers of composites (cf. *Figure 1-5*). Leisure boats are probably also the application where the layman is most likely to know that composites are extensively used. Almost all leisure craft—from the smallest dingy to competition powerboats and sailing yachts—have been manufactured from composites for many years. The reasons for this relative dominance of composites in leisure craft are several, but the dominating impetus is once again cost; composites boats are relatively inexpensive. One of the most significant reasons for the lower cost is that manufacturing of composite boats is amenable to mass-production (which with boats still translates into small numbers if one compares with the automobile industry) and that fewer craftsman's skills are required than to work with wood or metal. Production costs are also positively influenced by the fact that a mold to manufacture a boat is inexpensive and relatively simple to construct. It therefore makes economical sense to manufacture very short series or even one-of-a-kind boats. Compared to other material alternatives, the initial costs involved in starting to manufacture composite boats are very low, since few specialized tools or facilities are needed. The basic knowledge needed to get started with composites is quite quickly obtained, although it may take a lifetime to

become a professional. Yet another advantage is that composites place few restrictions on the all-important shape of the hull. From the owner's point of view it is finally extremely attractive that composite boats, relatively speaking, require very little maintenance since they do not rot or rust. Indeed, a great many of the very first composite boats made in the 1950s are still in use, largely unaffected by the elements.

Figure 1-17 shows a powerboat typical of an entire class of boats sprayed up from discontinuous glass-reinforced unsaturated polyester (see Section 4.2.1.2). While the hull of this type of rather small boat almost always is a single-skin laminate, deck and floorboards are often sandwich structures in order to obtain sufficient stiffness. Larger powerboats, such as that shown in Figure 1-18, are generally hand laid up; sandwich structures tend to be used throughout hull, deck, and floorboards of such boats (see Section 4.2.1.3).

At the other end of the spectrum are extreme competition powerboats and sailing yachts, such as that shown in Figure 1-19. In this category, no effort (or money) is spared in order to build the winning boat and the aim is almost always weight reduction. Both hull and deck of such boats are normally hand laid-up sandwich structures with high-performance continuous-fiber reinforced laminates and cores (see Section 4.2.1.3). While

Figure 1-17 Powerboat sprayed up from discontinuous glass-reinforced unsaturated polyester (see Section 4.2.1.2). The hull is a single-skin laminate, while deck and floorboards are sprayed up sandwich structures. The sandwich structures have an expanded polyvinyl chloride foam core, except at loading points where marine plywood is used. Some hatches are manufactured through resin transfer molding (see Section 4.2.3.2). Photograph courtesy of Ryds Båtindustri, Ryd, Sweden

Figure 1-18 Powerboat hand laid-up from glass-reinforced unsaturated polyester (see Section 4.2.1.3). Hull, deck, and most floorboards are sandwich structures with polyvinyl chloride foam core and laminates are reinforced with a combination of mats and fabrics. Photograph courtesy of Aplicator System, Mölnlycke, Sweden

Figure 1-19 Black Magic, New Zealand's challenge in the 1995 America's Cup in San Diego, is an example of advanced composites usage. Black Magic trashed the competition and won all races to ensure that the 1999 America's Cup will be held in Auckland, New Zealand. Photograph by Christian Février

manufacture of leisure boats is a relatively uncomplicated procedure, manufacture of competition boats more and more resembles techniques used in the aerospace industry. The same kind of trends largely apply also to the materials used; glass-reinforced unsaturated polyester is gradually replaced by high-performance materials such as carbon- and aramid-reinforced vinylester or epoxy, while low- to medium-performance cores are replaced by high-performance expanded polymer foams and sometimes even honeycomb cores. More recently and particularly in competition yachts, composites are becoming the material of choice also in masts, booms, and rigging, where true aerospace-grade materials (pre-impregnated carbon-reinforced epoxies) and manufacturing techniques (hand layup followed by autoclave crosslinking, see *Section 4.2.2*) are becoming the norm.

Composites have also made inroads into some specialized shipbuilding applications, where the sandwich concept with glass-reinforced unsaturated polyester laminates on expanded polymer foam or balsa cores is utilized. One example is surface-effect ships (SES), which are catamarans with curtains between the keels in bow and stern allowing an air cushion to be maintained between the keels; the air cushion lifts the hull out of the water to significantly reduce drag and thus allow high speeds to be reached (see *Figure 1-20*). Some SESs are capable of transporting up to four hundred passengers at speeds in excess of 50 knots. The largest composite sandwich SES built measures 40 by 15 meters. In this application composites help achieve a low enough weight to suspend an entire ship on an air cushion and hand layup is highly competitive since large structures are manufacturable and few look-alike SESs are built.

Figure 1-20 SES capable of transporting 341 passengers at speeds up to 45 knots. This SES is a sandwich construction with hand laid-up glass-reinforced laminates on a polymer foam core (see *Section 4.2.1.3*). Photograph courtesy of Brødrene Aa, Hyen, Norway

Composite sandwich ships are also used in military applications. For example mine-sweepers, or mine counter-measure vessels (MCMV), longer than 50 meters, wider than 10 meters and with displacements up to 400 tons have been built entirely from composites. In this application composite materials and wet hand layup offer substantial advantages. The non-magnetic material is desirable so as not to risk detonating magnetically sensitive mines, the foam core sandwich is damage tolerant to underwater detonations, and hand layup is once again highly competitive for size and series-size reasons.

Probably the most spectacular composite ship so far is the 72 m long single-hull stealth surface attack ship built for the Swedish Navy, see *Figure 1-21*. Apart from probably being the largest composite structure ever built, it is unusual as a marine structure in almost entirely utilizing carbon reinforcement in the sandwich laminates. Early analyses showed that for a given stiffness carbon-reinforced laminates are actually cheaper than glass-reinforced laminates, since the laminate thickness can be reduced to a third and

Figure 1-21 Artist's rendition of 72 m long surface attack ship built for the Swedish Navy. The ship is a sandwich structure with polyvinyl chloride foam core and carbon-reinforced vinylester laminates. Laminates and sandwich structure are manufactured simultaneously through vacuum-injection molding (see *Section 4.2.3.3*) for most of the structure, but hand layup (see *Section 4.2.1.3*) is also used to some degree. Drawing courtesy of Defense Materiel Administration, Stockholm, Sweden

labor costs are thus drastically lowered. Thinner laminates naturally also result in a lighter structure, allowing further weight savings in engines and drivetrain. The complete weight of the composite structure will be 150 tons of which 40 tons are carbon fibers, while the final displacement is expected to be around 600 tons. Four of these ships are currently on order and the first will be launched around the turn of the century.

1.5.3 Aerospace and Military Applications

Judging from *Figures 1-4 and 1-5*, aerospace and military applications would appear insignificant by weight, but both areas have been and certainly still are vital to the development of composites. One reason why aerospace and military applications are more relevant than they appear from statistics is that it is in these application areas that the most expensive raw materials are used. However, the main reason is that due to the extreme desire to obtain the ultimate in performance, most of our knowledge of composite design and all high-performance materials one way or another have their origins in these fields of application.

While the specific properties of composites are seldom seriously taken advantage of in road, rail, and water-bound vehicles, the opposite holds true in aerospace applications. Saved weight in a flying craft directly translates into increased load-carrying capability or performance enhancements and in fighter aircraft such performance enhancements may be literally the difference between life and death. Perhaps less obvious is the fact that composites can lower manufacturing cost in many applications due to the possibility of parts integration (as previously discussed for transportation applications). Yet another advantage is that composites have significantly better resistance to fatigue than light metals. Moreover, the radar transparency of glass-reinforced composites has long been used in aircraft radomes (nose cones), while a quite recently exploited aspect of composites is their inherent stealth properties (although much of the stealth technique lies in use of an angular geometry to reflect a minimum of radiation).

That the development of composites in aerospace applications is driven by military developments is particularly obvious in the United States (see *Figure 1-22*), although all modern military aircraft use significant amounts of composites (see *Figure 1-23*). The material choices (and often locations) in many military aircraft tend to be shrouded in secrecy, but as a rule composites are based on prepregged carbon-fiber reinforced epoxy that is crosslinked in an autoclave (see *Section 4.2.2*), although glass and aramid reinforcement as well as more exotic matrices than epoxies are also used to some degree. While many composites are single-skin laminates, sandwich components with honeycomb are in extensive use. Common polymer composite components on military aircraft include control surfaces (rudders, flaps, etc.), wing skins and substructures, leading edges, complete vertical and horizontal stabilizers, radomes, landing gear doors, access doors, weaponry, and external fuel tanks.

Figure 1-22 The Lockheed YF-22A Advanced Tactical Fighter consists of significant amounts of both thermoplastic (13 weight percent) and thermoset (10 weight percent) composites [5]. Composite components include wing skins and spars, as well as skins of vertical and horizontal tails. While the production F-22 was expected to have 35 weight percent composites [5], the first deliveries contain less than 20 weight percent composites, partly due to manufacturing difficulties [6]. Photograph courtesy of Boeing Commercial Airplane Group, Seattle, WA, USA

Figure 1-23 Up to 30 percent of the structural weight of the multi-role combat Saab Gripen (Griffin) is polymer composite. The Gripen is likely unique in that the entire wings, including all of the wing substructure, are composite. Other composite components include vertical stabilizer, canard wings, control surfaces, access doors, main landing gear doors, and radome. Components are hand laid up from carbon-reinforced epoxy prepreps and crosslinked in an autoclave (see *Section 4.2.2*). Extensive use is made of the sandwich concept using aluminum honeycomb core. Photograph courtesy of Saab Military Aircraft, Linköping, Sweden

Composites are also much used in civilian aircraft applications, but introductions of new composite components are for safety reasons considerably more cautious. Also in commercial airliners the potential weight saving is highly valued; it has been calculated that an excess kilogram in an airliner approximately requires another 130 liters of fuel per year [7], which instead could be used to increase range or payload. However, manufacture of airliners is such a cost-conscious business that weight savings are often not worth an increase in production cost, so unless weight savings are substantial, reduction in manufacturing cost is a more important motive. Consequently, the potential for parts integration translated into cost is one of the strongest arguments in favor of composites in civilian aircraft as well. As an example, the metal rudder of Airbus Industrie's A300 and A310 wide-body jets was already in 1983, and at similar cost, replaced by a carbon-reinforced epoxy sandwich with honeycomb core. This change resulted in a 22 percent weight decrease and reduction in the number of parts from over 17,000 to 4,800 (since bonding eliminates rivets) [7].

Not surprisingly composite applications in airliners are not entirely unlike those in military aircraft; they include control surfaces, parts of wing skins, leading edges, entire vertical and horizontal stabilizers, fairings, engine nacelles, thrust reversers, propellers, radomes, landing gear doors, access doors, and large parts of cabin interior and cargo compartments. While American aircraft manufacturers tend to lead the way in terms of composites use in military applications, European aircraft manufacturers, particularly Airbus and Avions Transport Regionale (ATR), appear to be ahead in civilian applications (see *Figure 1-24*), although Boeing is increasing its use of composites for each new model (see *Figure 1-25*). The most advanced composite structures in civilian aircraft are the all-composite empennages, i.e. entire horizontal and vertical stabilizers, including control surfaces, found on all Airbus models since 1987. There is now talk of Airbus planning to make wings and eventually the entire fuselage from composites. Currently, Airbus's largest models, the A330 and A340, are said to contain in excess of 15 tons of composites each [7].

Virtually all composite components in civilian aircraft are hand laid up from epoxy prepregs with carbon, aramid, and glass reinforcement, although automated tape layup is used for some Boeing components (see *Section 4.2.2*). Many composites are sandwich components, almost always with Nomex honeycomb core. Hand layup strongly dominates manufacturing due to the relatively short series, but automated layup techniques are used to a limited albeit increasing degree.

Although their share of composite consumption is small compared to commercial airliners, light sport aircraft, such as gliders, small propeller planes, and various ultralight aircraft deserve to be mentioned. While mass-produced small propeller aircraft tend to employ conventional materials, a range of light sport aircraft are built almost entirely using composites. It has

Figure 1-24 Airbus has largely been at the forefront in terms of composites in commercial aircraft for a number of years. In 1983, Airbus introduced a single-piece composite rudder, two years later the entire vertical stabilizer was converted into composites, and since 1987 also the horizontal stabilizer has been composite. Now all Airbus models, including the A321 in the figure, have all-composite empennages. Composites are also used in control surfaces, fairings, engine nacelles, thrust reversers, radomes, floor support struts, and most of cabin interior and cargo compartments, to mention but a few applications. Photograph courtesy of Airbus Industrie, Blagnac, France

Figure 1-25 The Boeing 777 is the first American commercial aircraft with composite empennage. Skin panels, stringers, angles, brackets, etc. are manufactured through automated tape layup (see Section 4.2.2) [8]. Other composite components in Boeing aircraft include the types mentioned for Airbuses above. Photograph courtesy of Boeing Commercial Airplane Group, Seattle, WA, USA

been estimated that approximately 80 percent of all such composite aircraft, which number in excess of 13,000, have been built in Germany. It is noteworthy that most of these have been built using manufacturing techniques more similar to those used in boat building than those normally associated with aircraft manufacture [7].

Modern helicopters make even greater use of composites than aircraft. While for example helicopter main and tail rotor blades have been glass-reinforced composites for many years, an increasing number of metal components are replaced by composites to reduce manufacturing cost and save weight. In new helicopter models on both sides of the Atlantic, such as the Eurocopter Tiger attack helicopter and the NH 90 freighter (see *Figure 1-26*) as well as the Boeing V-22 tilt-rotor and Sikorsky RAH-66 Comanche helicopters, the concept of all-composite fuselages is being implemented, although the future of all these helicopters appears a little uncertain at the time of writing. That composites are being used extensively in helicopters, which jokingly are referred to as flying fatigue machines, is testament to the excellent fatigue characteristics of composites.

An application area that consumes very small amounts of polymer composites, but where gains from weight savings are even greater than in aircraft, is spacecraft. Considering the immense cost of launching a kilogram of payload into space, the efforts going into weight-optimizing the structures of both payload and launch vehicle (see *Figure 1-27*) are far-ranging and they

Figure 1-26 The Eurocopter NH 90 is a near-complete composite structure, which relies on sandwich structures with carbon-reinforced epoxy faces on Nomex honeycomb core for the primary structure, although glass- and aramid-reinforced faces are also used to some degree. One of the main reasons for using composites, which are hand laid up and autoclave consolidated (see *Section 4.2.2*), is that overall manufacturing costs are sharply reduced due to far-ranging parts integration.

Photograph courtesy of Eurocopter Deutschland, München, Germany

thus contain a lot of composites. An extreme example of this is Orbital Sciences Corporation's launch vehicle Pegasus XL, which is a near-complete composite structure. The Pegasus, which is a three-stage solid propellant rocket, is air-launched from an aircraft and roughly halves the cost of boosting payloads into orbit compared to earth-launched competitors.

Figure 1-27 The European Space Agency's Ariane 5 launch vehicle makes extensive use of composites. Photograph courtesy of Aerospatiale, Les Mureaux, France

Composites are particularly well suited to applications where the primary load case is (internal) pressure. The manufacturing technique of filament winding (see *Section 4.2.5*) has been most successfully applied in manufacturing solid rocket motors, rocket nozzles, and fuel tanks for secondary propulsion systems (see *Figure 1-28*). This is the same concept as used for CNG tanks for AFVs and in auxiliary fuel tanks mounted under the wings of military aircraft, although in these two applications tanks are normally cylindrical instead of spherical. Nevertheless, it deserves to be pointed out that many components of a launch vehicle, not to mention a space shuttle which is to be reused, are exposed to such high temperatures that polymer matrices may no longer suffice. For such applications, ceramic and carbon matrices have been developed, but these unique classes of composite materials are only very briefly discussed in this book.

Figure 1-28 Tanks for high-pressure fuel on the central cryogenic stage of the Ariane 5 launch vehicle. The carbon-reinforced spherical tanks are filament wound onto a gas-impermeable metal liner (see Section 4.2.5). Photograph courtesy of Aerospatiale, Les Mureaux, France

Figure 1-29 Satellite antenna designed to eliminate dimensional changes due to temperature variations. The structure is a hand laid up and autoclave consolidated (see Section 4.2.2) sandwich with honeycomb core and carbon-reinforced epoxy laminates. Photograph courtesy of Saab Ericsson Space, Göteborg, Sweden

Depending on whether they are exposed to direct sunlight or in the earth's shadow, satellites are exposed to very large temperature differences that could cause dimensional changes to antennae which could completely distort telecommunication signals for example. Satellite antennae are excellent examples of how composites may be designed to have virtually no thermal expansion over a very wide temperature range (see *Figure 1-29*). Solar arrays, general panels, tubular truss members, etc. on satellites are also often polymer composites.

Composites are also being introduced into a range of non-aerospace military applications. Arguments in favor of composites in such applications include lower weight, energy absorption, stealth (cf. *Figure 1-21*), and many others. The lower weight is mainly employed to improve portability of weapons (see *Figure 1-30*), bridges, radio antennae, etc., while the good energy absorption is used in helmets and in the armor of for example personnel carriers and even tanks.

Figure 1-30 One of the world's best-selling composite launch tubes for delivering antitank projectiles. The tube is filament wound from glass-reinforced epoxy without use of a liner (see *Section 4.2.5*). Although this is a disposable weapon, the tube would be capable of delivering 10–20 projectiles. Photograph courtesy of Bofors Weapon Systems, Karlskoga, Sweden

1.5.4 Construction Applications

While a precise definition of this category is difficult, it is herein taken to include the categories of “Construction”, “Industrial/agricultural equipment”, and “Corrosion-resistant equipment” of *Figures 1-4 and 1-5*. With this categorization, this is by far the most important area of composite applications (by weight). While civil engineers by and large appear to be quite uninterested in looking beyond conventional civil engineering materials, the situation is ever so slowly changing and some individuals in the profession are starting to see the advantages offered by composites.

In civil engineering applications light weight is seldom sought (after all, the standard is concrete and steel, so the industry is used to hauling a lot of weight), although there are some examples to the contrary. Light weight may prove advantageous when transportation is a problem and when heavy machinery is not available to aid in assembly. There are several examples of bridges being erected in national and state parks in the United States where trucks or helicopters could not or were not allowed to operate. Bridge components therefore had to be carried by man or mule to the site of erection, which hardly would have been possible with a steel or concrete design. Once the construction material is on site, the actual erection is significantly simplified if all components can be moved by workers instead of heavy machinery. Indeed, the most spectacular bridge application to date, the Aberfeldy footbridge over the river Tay in Scotland (see *Figure 1-31*), was

Figure 1-31 The Aberfeldy footbridge over the river Tay in Scotland is 113 m long, has a main span of 63 m, and a deck width of 2.2 m. The entire deck structure, hand rails, and A-frame towers are pultruded glass-reinforced unsaturated polyester (see *Section 4.2.6*) and the cable stays polyethylene-coated Kevlar ropes. The deck structure is assembled from a modular system of 0.6 m wide and 6 m long hollow sections weighing 66 kg each. With the exception of the small concrete foundations, the entire bridge is composite [9]. Photograph courtesy of Maunsell Structural Plastics, Beckenham, Kent, UK

erected in 1992 by eight students in ten weeks without the use of heavy machinery (except for the small concrete foundations) [9]. Light weight was also one of the main reasons for choosing a composite solution for the world's first drawbridge for vehicular traffic (see *Figure 1-32*), since this meant that both lifting tower and counterweight could be eliminated.

Figure 1-32 The Bonds Mill Bridge on the Stroudwater Navigation canal in England is the world's first drawbridge for vehicular traffic. The bridge is assembled from the same modular system as used for the Aberfeldy Bridge (cf. *Figure 1-31*). Photograph courtesy of Maunsell Structural Plastics, Beckenham, Kent, UK

Composites are being predicted to have a promising future in bridge applications in the United States based on the observation that its bridges, many of which were built in a rather short time frame, are decaying at a rapid rate and will need to be replaced at an equally rapid pace. Rather than closing off a highway overpass for months to build a new concrete deck, the argument goes that composite decks could be assembled beside the existing overpass (while it is still in use) and when ready, the old deck would rapidly be demolished and the complete composite deck could then be lifted in place by a single crane in a matter of hours. While this potentially enormous application area is indeed alluring and a few full-scale composite bridges are being built, it so far largely remains elusive.

A bridge-related application area that is seeing quite a lot of full-scale trials is so-called retrofitting of earthquake-damaged bridge columns, mainly

in California. Following earthquakes, many steel-reinforced concrete columns of bridges and overpasses end up cracked. Unless seriously damaged, such columns can still perform satisfactorily if they are just laterally supported. Previously such retrofitting entailed enclosure of the column in two custom-made half-cylinder steel shells which then were welded. More novel approaches include filament winding (see *Section 4.2.5*) of a composite jacket onto the column using a machine traveling around the column. Similar concepts include wrapping of dry reinforcement onto the concrete followed by subsequent reinforcement impregnation using vacuum-injection molding (see *Section 4.2.3.3*). This latter concept, as well as that of bonding of already crosslinked composites onto decaying concrete structures, is also used outside of North America.

While light weight may often be a positive side effect for reasons already discussed, a more common argument in favor of composites in construction is that dramatic improvements in corrosion resistance, and indirectly reduction or elimination of the need for maintenance, are obtainable. These may prove very convincing arguments for structures in chemical plants (see *Figure 1-33*), waste water treatment plants (see *Figure 1-34*), harbors, and other corrosive environments. Many such construction applications, which consume large amounts of composites, employ general and often standardized construction members (such as those shown in *Figures 1-33* and *1-34*) in full analogy with the standard procedure for steel beams.

Figure 1-33 Standardized I-beams pultruded from glass-reinforced unsaturated polyester and vinyl ester (see *Section 4.2.6*) used as platform and walkway support in chlorine manufacturing operation. Photograph courtesy of MMFG, Bristol, VA, USA

Figure 1-34 Grating and handrails pultruded from glass-reinforced vinylester (see Section 4.2.6) used in municipal waste water treatment plant. Photograph courtesy of MMFG, Bristol, VA, USA

Figure 1-35 Subsea structure to protect the wellhead of an oil well, for example from fishing trawls. This sandwich structure, which consists of glass-reinforced laminates on a polyvinyl chloride foam core, was hand laid up (see Section 4.2.1.3). Photograph courtesy of Brødrene Aa, Hyen, Norway

Other applications where large amounts of composites are used include building panels, piping, gasoline and water tanks, wine-maturing vats, silos, etc. In particular off-shore applications, i.e. oil-exploration platforms where the environment is extremely corrosive, are expected to become major application areas for composites in the near future. However, partially for fire safety reasons this is a very conservative industry and composites are only slowly being accepted. Current off-shore composite applications include seawater piping systems for fire fighting, fire-protection panels (sandwich structures with ceramic core), grating, ladders, handrails, and subsea wellhead protection structures (see *Figure 1-35*).

1.5.5 Electrical and Sanitary Applications

From a structural point of view some of the most mundane, albeit by consumption quite important (cf. *Figures 1-4* and *1-5*), composite applications are to be found in electrical and sanitary environments.

In electrical applications, the dielectric strength of glass-reinforced composites is of great interest and generally much more important than the structural capabilities (which are nevertheless valued in some cases). Applications in electrical and electronic areas include circuit boards, equipment housings, transformer spacers, and cable trays to mention a few. One particularly large order of cable trays was the 450 km required for the tunnel (or, rather, three tunnels) under the English Channel. For electricians, tool handles, booms for "cherry picker" trucks, and last but not least ladders are common applications; ladder rails are one of the biggest composite applications in North America (see *Figure 1-36*). The attraction of eliminating direct electrical contact between electrician and potentially hot wires as well as between electrician and ground is obvious.

Sanitary applications are dominated by shower enclosures (see *Figure 1-37*), bath tubs (see *Figure 1-38*) and spas, sinks, and cabinets, although there are many other applications. Related applications include bird baths, fish ponds, small pools, and water slides. In such applications it is mainly the design freedom and the possibility of economically manufacturing short series that are the main advantages.

1.5.6 Sports Applications

Second perhaps only to "fiberglass" boats in terms of public awareness, sporting goods, such as "graphite" golf clubs, "Kevlar" tennis racquets, and "ceramic" skis, are well-recognized and accepted composite applications. Although a method to pultrude (see *Section 4.2.6*) composite fishing rods was already patented in 1951, the real breakthrough of composites in sporting goods has taken place in a very limited time frame and has all but eliminated traditional materials. It is now virtually impossible to buy a (new) tennis racquet, slalom ski, or surfboard made from wood.

Figure 1-36 Ladder with (vertical) rails pultruded from glass-reinforced unsaturated polyester (see Section 4.2.6). Photograph courtesy of MMFG, Bristol, VA, USA

Figure 1-37 Two-piece shower stall with thermoformed acrylic surface film backed up by a sprayed-up glass-reinforced unsaturated polyester structure (see Section 4.2.1.2)

Figure 1-38 Corner bath tub with acrylic surface film backed up by a sprayed-up glass-reinforced unsaturated polyester structure (see Section 4.2.1.2)

While there are many reasons for this massive dominance of polymer composites, the main ones are fashion, vastly improved performance, lower weight, in some cases lower cost, and durability. In many cases it is difficult to ascertain whether the exclusive “high-tech” image of composites or real performance enhancements is the deciding factor since the vanity of man, particularly in sports, means that image often overshadows rational reasoning. Case in point, put a saw to your old slalom skis that proudly proclaim that they contain Kevlar or carbon reinforcement to enhance performance, and you may find that there are only a dozen such fibers in the ski, whose effect on performance thus is highly questionable. Nevertheless, improvements in performance and weight are in most sports applications real (the author has still not forgotten his first game of squash with a composite racquet; it was a completely different game).

While composite alternatives in most cases are more expensive than traditional solutions (where there are any still left), the reverse holds true in some cases. For example, split-cane flyfishing rods are significantly more expensive than carbon-reinforced epoxy alternatives, since so many craftsman hours go into painstakingly bonding precision-machined bamboo pieces into a split-cane rod. Cost is nevertheless often secondary; who is not prepared to pay an arm and a leg to beat his tennis partner or to improve his golf game?

Figure 1-39 Virtually all modern skis are elaborate composite sandwich structures. The figure shows the construction of a cross-country ski, but in terms of materials and general construction principles slalom skis are similar. Apart from the running base and cap which are generally unreinforced thermoplastics, the most common material is glass-reinforced epoxy, although high-performance reinforcements are used in top-of-the-range models. Cores are expanded polymer foams, wood, or in some cases a mere cavity. The objective is generally to achieve highest possible flexural and torsional stiffness at lowest possible weight and cost. Drawing courtesy of Madsus, Biri, Norway

The example of flyfishing rods illustrates that the fashion factor can be reversed since the traditional solution is the most exclusive and, if you ask a flyfishing aficionado, also the better. It also illustrates how a move from natural to synthetic materials reduces the degree of craftsman skills that go into manufacture; composites have moved sporting goods manufacture from the craftsman's shop into an industrial environment (although considerable craftsman skills are certainly still required). The same goes for the raw materials used in the respective cases; synthetic materials are clearly more amenable to mass production. The durability advantage is also relevant, since for example wooden squash racquets and bamboo flyfishing rods are not only expensive, they are also very fragile.

There are clearly countless composite application examples in sporting goods. A non-exhaustive list includes golf clubs, snow skis (see *Figure 1-39*), ski poles, water skis, surf boards, windsurfing boards, kayaks and canoes, bicycles (see *Figure 1-40*), helmets, fishing rods, crossbows and arrows, all kinds of racquets, various hockey clubs, and shoes.

Figure 1-40 Prototype bicycle manufactured from carbon-reinforced polyamide. The tubes of the frame are filament wound (see *Section 4.3.4*), while the connecting joints are hand laid-up and autoclave consolidated (see *Section 4.3.1*). Photograph courtesy of Institut für Verbundwerkstoffe, Kaiserslautern, Germany

1.5.7 Other Applications

There is little doubt that one could devote an entire book to composite applications, but only two more areas will be mentioned. The first one is in medicine, where composites for quite some time have been used in patient support tables in X-ray machines. These tables offer great stiffness while still being transparent to the radiation in order not to obscure the radiograph. Composites are also being investigated for artificial joints to replace the more conventional metal components used in, for example, artificial hip joints. A problem with inserting a titanium hip implant into the femur is that the stiffness of the implant is so much greater than that of the bone, which gradually leads to bone deterioration. With composites the stiffness can be tailored to that of the bone to eliminate this problem. Some composite material systems are also biocompatible, i.e. they are not repelled by the body.

Another application area where composites are being used to a greater degree is in external joint supports tailored to the individual; such supports have become popular among skiers with bad knees. A similar application area with great potential is in prostheses where light weight and stiffness are essential. In both these areas the possibility of manufacturing one-of-a-kind custom-fit components is critical to the success of the composite alternative.

A somewhat unusual composite application is in musical instruments, where string instruments so far have received the most attention. With careful design and manufacture an acoustic guitar, or for that matter any string instrument, can be made to satisfy the pickiest musician. Apart from the possibility of tailoring the instrument to whatever desire the customer may have, there are advantages in that the instrument is not sensitive to climate changes or transportation damage and that no rare woods on the brink of extinction are used.

1.6 Book Contents

The background to this book is the author's belief that "designers should wear a manufacturer's hat," to quote Burt Rutan, who is one of the world's most imaginative aircraft designers [10]. While there are several textbooks and engineering guides dealing with various aspects of polymer composite design, few texts deal with the aspects following the design process. This book provides an introduction to the most significant issues of the post-design process and most notably manufacturing-related aspects. The treatment is limited to composites with polymer matrices. While the emphasis throughout the book is on load-bearing, essentially meaning continuous-fiber reinforced, composites, some techniques and applications relevant to non-structural composites are included where they are closely related to those relevant to structural composites.

To be able to comprehend dominant mechanisms in composites manufacturing, a basic understanding of the behavior of the constituents is required; such an understanding may be obtained from *Chapter 2, Constituent Materials*, which emphasizes processability and property issues. Although the chapter inevitably involves some polymer physics and chemistry, only a very rudimentary prior knowledge of chemistry is required to follow the treatment. *Chapter 3, Properties*, dresses the qualitative material characteristics discussed in *Chapter 2* in numbers. *Chapter 3* is mainly intended to be a rudimentary data base for preliminary design studies or homework problems, but also briefly touches on the anisotropy of composites.

The main chapter is *Chapter 4, Manufacturing Techniques*, where the commercially most relevant and some emerging manufacturing techniques are treated in some detail. The emphasis of this treatment is on providing the reader with sufficient insight into the different techniques to enable him to select technically and economically feasible techniques for a composite design, but also to create an understanding for the limitations a given material system and manufacturing technique place on component design. It is not the intention of this chapter to provide such detailed knowledge of the treated techniques that the reader can start manufacturing composites without delving deeper into the literature; the intention is rather to provide a comprehensive overview of possibilities and limitations of different materials and techniques.

Chapter 5, Secondary Processing, deals with the normally inevitable issues of machining, joining, and surface finishing as well as repair. An integral part of any manufacturing operation is *Quality Control and Characterization*, which is the topic of *Chapter 6*. This chapter concentrates on issues likely to arise in a manufacturing environment and largely ignores the equivalent issues related to composite constituents.

The two final chapters deal with topics that are becoming ever more relevant. While recycling may not yet be a major concern for designer and manufacturer, it soon will be in many applications due to legal requirements. *Chapter 7, Recycling*, gives an overview of existing recycling techniques for composites. *Chapter 8, Health and Safety*, finally, provides an overview of the dangers that may be present in a composite manufacturing environment and discusses appropriate protective measures.

This is not the first textbook or engineering guide to composite-manufacturing related activities, but this one is believed unique in its comprehensiveness. The main intention of the author is to raise the awareness of present and future designers of composite-manufacturing related activities so that they can become more knowledgeable in these areas and thus better designers. It is also the author's hope that this book may serve to raise the interest in composite manufacturing and to provide a baseline for further work in the field.

1.7 Outlook

Looking into the crystal ball, there are several interesting developments on the horizon. These developments may essentially be divided into increasing use of existing materials and technologies, and development or invention of new materials and technologies.

Looking first at the former, there is great scope for increased use of current technology in existing applications as well as introduction into completely new areas. Considering the applications discussed in *Section 1.5*, the technology obviously is there to make the all-composite automobile, ship, aircraft, bridge, etc. Then why are such all-composite designs so rare? While part of the answer lies in lack of experience, general conservatism, legal requirements, and liability issues, the main reason is cost. Only in more or less cost-insensitive areas such as military applications and sporting goods is the buyer prepared to pay extra for small gains in performance. Moreover, if a composite solution may provide long-term savings for the owner but the up-front cost is notably higher, it probably will not sell well anyway; private owners and shareholders alike tend to expect a rather rapid return on invested capital.

There is consequently a great need for increased cost-effectiveness in all stages of design and manufacturing of both raw materials and composite components. Particularly in the automobile industry the drive to lower cost and increase production rate is strong. One common way to reduce cost is through economies of scale, i.e. mass production. A couple of application areas that are being seen as aiding in this development are general construction and off-shore applications. If for example the highway authorities in the United States were to adopt the previously discussed concept of composite bridge decks, or if significant portions of the mammoth oil platforms used off-shore were to be made from composites, material consumption would increase drastically with likely positive side-effects of lower raw material prices and a more widespread acceptance of composites in construction.

While lifetime fuel consumption of vehicles, and in particular privately owned automobiles, rarely is given significant consideration at the time of purchase (unless there are extreme differences between candidate vehicles), rising fuel prices and legal incentives will gradually mandate more fuel-efficient vehicles. This is a promising development for composites, since lighter vehicles are synonymous with improved fuel efficiency. There is also a movement worldwide to include the overall resource utilization of a component or structure in a cradle-to-grave analysis. Such a life cycle assessment (LCA), which is briefly discussed in *Chapter 7*, considers all energy and resources that go into, for example, a vehicle, from raw material extraction and refining, to vehicle manufacture, use, and post-life recycling or disposal. LCAs are usually in favor of composite solutions, both due to

their lower weight and because relatively little energy goes into raw material extraction and refining of composite constituents when compared to, for example, aluminum (which offers another efficient way of lowering the structural weight of a vehicle).

A related development is the increased interest in recycling. While recycling of paper, aluminum, steel, glass, etc. has become common, recycling of composites is a very recent occurrence. The development has nevertheless been rapid, mainly prompted by German recycling laws, and it is clear that in the near future recycling will be required in a range of applications, particularly in the automobile industry. While there are already technically feasible recycling techniques for all types of composites, the main stumbling block is the economical feasibility. Much work can thus be expected in improving existing recycling techniques and invention of completely new ones, both from technical and economical perspectives.

The development of new constituent materials appears to have slowed down in recent years due to the end of the cold war, recessions, and general belt-tightening. There is nevertheless still quite some work going on and improvements are being seen in properties of both fibers and matrices. In terms of reinforcements these are most notable in carbon fibers which are starting to push the envelope of elastic moduli to in excess of an impressive 1,000 GPa (cf. steel at 200 GPa and aluminum at 70 GPa), while at the other end of the spectrum the price of standard carbon fiber grades is coming down to gradually make carbon a commodity reinforcement.

Some of the biggest problems with polymer matrices are their poor temperature tolerance (when compared to metals), that many are brittle, and that most are demanding in terms of processing requirements. Developments are therefore constantly underway to raise the continuous-use temperatures of matrices, particularly for use in aerospace applications. At extreme temperatures where polymer matrices no longer suffice ceramic, metal, and carbon matrices are seeing increased use. Most conventional polymer matrices are thermoset and therefore inherently brittle. Although much successful work has been and still is going into modifying thermosets to alleviate this problem, another increasingly interesting possibility is offered by thermoplastic matrices which are inherently ductile. Almost all polymers are difficult or time-consuming to process and there is consequently ample room for improvements in processability. Considerable efforts are going into reducing times and temperatures required for crosslinking of thermosets and into reducing melt viscosities of thermoplastics.

Another aspect of thermoplastics is that due to the absence of chemical reactions during manufacturing, processing can potentially be significantly more rapid than with thermosets, which must be given time to undergo chemical conversion. This opportunity has not been lost on the automobile industry in its quest for more rapid manufacturing, and compression molding of thermoplastic composites (see *Section 4.3.3.1*) is rapidly gaining

ground. Although a major breakthrough for thermoplastic composites was predicted in the 1980s and early 1990s, this has not—with the exception of compression molding—been realized. It is nevertheless likely that thermoplastic composites will gradually see wider acceptance due to both manufacturing and property advantages.

While most techniques for manufacturing of thermosets are relatively mature technologies, there is still scope for improvements in existing techniques and invention of new or hybrid techniques. One such example is the emerging technique of embedding sensors within a crosslinking component to enable tailoring of processing conditions to each component. This technique only makes economical sense for very expensive components, say a wing skin for a military aircraft, but may lead to improved component properties, reduced scrap ratio, and more rapid processing. With thermoplastics the situation is the opposite; most technically feasible techniques developed to date require further research and development work before they can expect widespread commercial acceptance. Developments in manufacturing technology are normally gradual rather than incremental. Developments may be in terms of increased automation, reduction in cycle time, and lowering of mold cost, but are more commonly in terms of improvements in component properties, such as geometrical complexity, surface finish, fiber content, repeatability, etc.

Health and safety is becoming more relevant and the increasing awareness of hazards posed by active chemistry influences the developments in both materials and manufacturing techniques. In this respect thermoplastics offer significant improvements over thermosets, since no active chemistry is involved in processing and health hazards are thus essentially eliminated. With thermosets closed-mold techniques (where the matrix is contained within closed molds to sharply reduce operator exposure) are increasingly being favored over the more conventional open-mold techniques.

Particularly in the aerospace industry, work is underway to develop so-called smart materials, in this case smart composites, although they are probably still a fair way from commercial application. Smart composite concepts include components with embedded sensors and adaptive structures. In the former case sensors, for example optical (glass) fibers, are embedded within the reinforcement to enable monitoring of loads and structural integrity during use. These sensors may very well be the same ones used to optimize manufacturing, as discussed above. While a composite through clever reinforcement orientation can be designed to increase its stiffness as load increases, an adaptive component allows independent changes in some property, such as stiffness or eigenfrequency, based on input from a control system, in order to optimize structural performance.

Composites are indeed very exciting materials in the extensive opportunities they offer in terms of tailoring of component or structure properties. However, at the same time, these possibilities require that both designer and

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