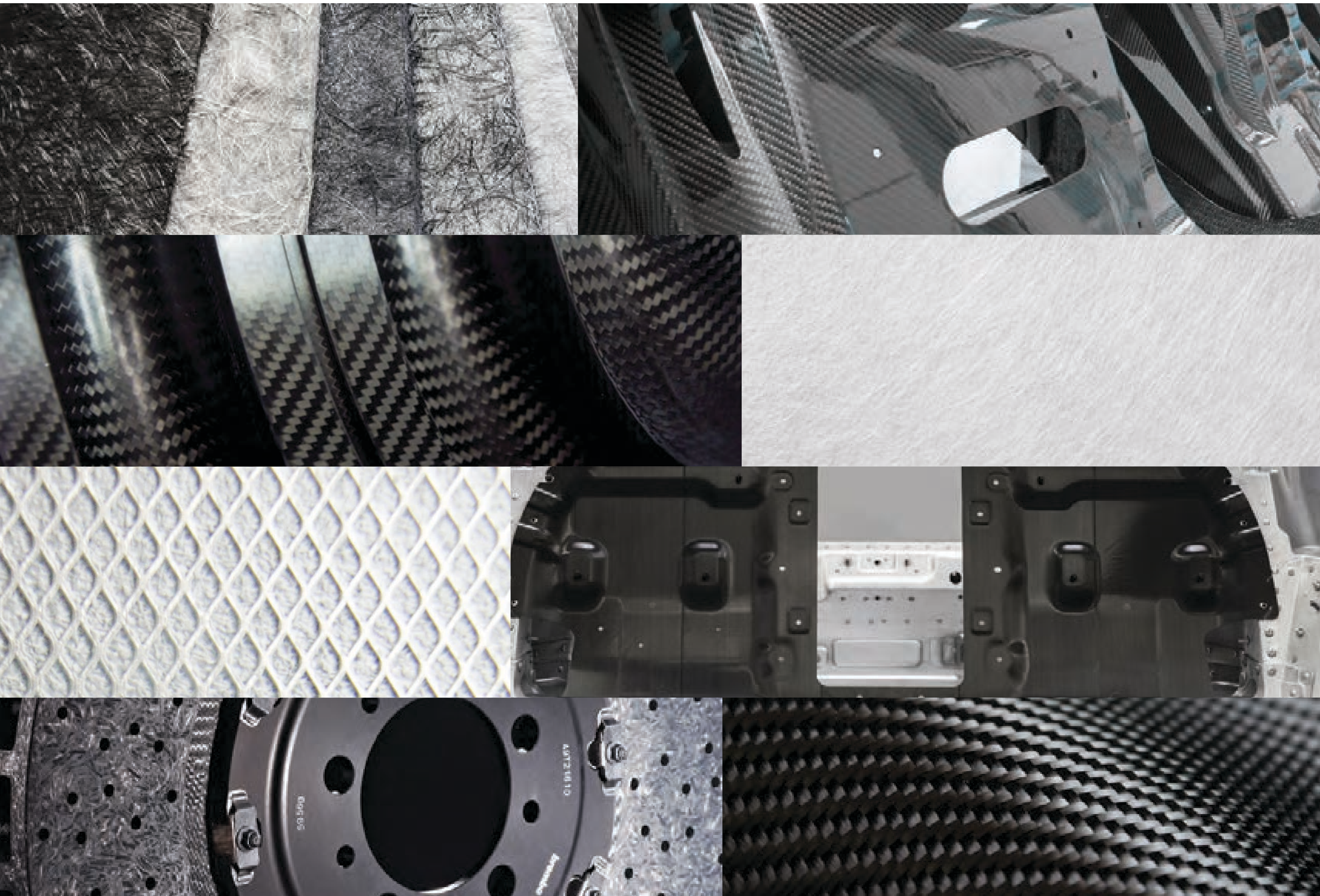
Second Edition

Essentials of ADVANCED COMPOSITE FABRICATION AND REPAIR

Louis C. Dorworth
Ginger L. Gardiner
Dr. Greg M. Mellema



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AVIATION SUPPLIES & ACADEMICS
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Essentials of Advanced Composite Fabrication and Repair
Second Edition
by Louis C. Dorworth ▪ Ginger L. Gardiner ▪ Dr. Greg M. Mellema

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Preface

NEARLY DOUBLING the content of the first edition, this second edition of ***Essentials of Advanced Composite Fabrication & Repair*** covers a wider range of contemporary technical material and is designed to function as both a textbook for Abaris Training and other technical schools teaching composites, and as an "essential" resource for everyone else, from novice to professional, involved in the advanced composites industry.

Initially produced as a spiral-bound composition of excerpts from various technical documents gleaned from the Lear Fan, Ltd. program and other pioneer leaders of the early 1980s, the original text was used to support a single Abaris course, "Inspection and Repair of Composite Structures." Over the next twenty years, the book expanded and developed as more innovative materials and technologies emerged and as Abaris added relevant new courses. By 2005 the authors realized the need for a "real" textbook and began a collaborative effort with the publisher to formalize the content. In 2009, the first edition textbook was published and put to use throughout the industry.

The composites industry moves fast, and by 2015 the authors once again realized the need for a thorough update of the content, thus beginning a new journey to identify what had changed in the past decade and how to include it in this new edition. It turned out that much had changed and much had remained the same. Over countless days and nights the authors spent time taking it all in from industry sources, purging content no longer relevant, and weaving together new content and illustrations in a logical order that the reader can easily follow and understand.

Like the first edition, this book starts with an introduction to composites and then takes a deep dive into the constituent materials such as fibers, matrix resins, nano, and core materials, and the cure or processing of them. This is followed by chapters that cover basic design considerations, molding methods and practices, tooling, testing, bonding, machining and drilling, repair, and much more. In addition, the publisher maintains an updatable webpage for the textbook, as a collection point for future downloadable materials and further notes the authors want to share with readers (www.asa2fly.com/reader/composite).

It is the sincere desire of the authors that readers gain a deeper knowledge and a better understanding of the subject and are empowered to put this information to use immediately on their projects, and in their workplace and career.

About the Authors

LOUIS C. (LOU) DORWORTH is the Direct Services Manager for Abaris Training Resources, Inc., where he currently manages all marketing and training activities worldwide. By trade, he is a composite materials and process (M&P) specialist with experience in research and development (R&D), manufacturing engineering, tool design/engineering, tool fabrication, and repair.

Lou has been involved in the advanced composites industry since 1978, starting in aerospace as a toolmaker and part-time M&P technician for the Lear Fan 2100 program in Reno, NV and going on to work in the industry for another decade. Lou has been associated with Abaris since its inception in 1983 and began his teaching career at Abaris in 1989.

Lou has been a professional member of the Society for the Advancement of Material & Process Engineering (SAMPE) since 1982, a senior member of the Society of Manufacturing Engineers (SME) since 1997, and a member of the Society of Plastics Engineers (SPE) since 2014. He currently serves as co-chair of the SAMPE Technical Excellence Sub-Committee for Hybrids and Bonding and is an advisor to several conference and workshop steering committees within these technical organizations.

GINGER GARDINER has worked in the composites industry since 1990. She has a degree in Mechanical Engineering from Rice University and began her career as a technical marketing representative in DuPont's Composites Division for KEVLAR and NOMEX products in aerospace and marine applications. After leaving DuPont, Ginger formed Vantage Marketing Services, providing market and product development consulting for companies such as Hoechst-Celanese and Ciba-Geigy, and also developed and marketed technical conferences. She also wrote articles for several magazines, including *Professional BoatBuilder*, and began writing for *Composites Technology* and *High Performance Composites* magazine in 2006. She has worked as Senior Editor of the now combined *CompositesWorld* magazine since 2013.

GREG MELLEMA, Ph.D. is Assistant Professor at Embry-Riddle Aeronautical University teaching a variety of maintenance-related courses at both undergraduate and graduate levels. Additionally, he conducts research focused on Advanced Composites as well as Maintenance Human Factors. He has been an active Airframe & Powerplant mechanic since 1988 and holds an Inspection Authorization (IA) from the FAA as well.

Dr. Mellema has over 30 years' experience working on both manned and unmanned military and civilian aircraft with a special emphasis on manufacture and repair of advanced composite structures. During that time, he worked extensively with the U.S. Army's Test and Evaluation Command and later founded the Army's Advanced Composites Lab at Redstone Arsenal. There he designed and built prototype advanced composite parts, as well as modernized composite repair tools, processes and procedures across all Army aviation platforms.

Greg holds a B.S. degree in Professional Aeronautics, an M.S. in Aeronautical Science and a Ph.D. in Aviation from Embry-Riddle Aeronautical University. He is also a member of SAMPE, AMT Society, and holds certifications in composites/composite repair from both SAE and CertTEC.

Editor's Note

THE DESIGN OF THIS TEXTBOOK takes advantage of visual elements to aid the reader's navigation through the narrative: a yellow "dot" helps identify the numbered Figures referred to in the text, as well as, in most cases, a gray "bar" along the outside edge of the page to differentiate between illustration content and the narrative content. Tables are numbered separately to distinguish them from the drawn and photographic illustrations. Footnotes are contained at the bottom of pages where they fall in the text, and further bibliographic references are listed at the back of the book. In addition, a short main-topic contents list is added to the chapter-start pages.

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1

Composite Technology Overview

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2 Examples of Typical Applications
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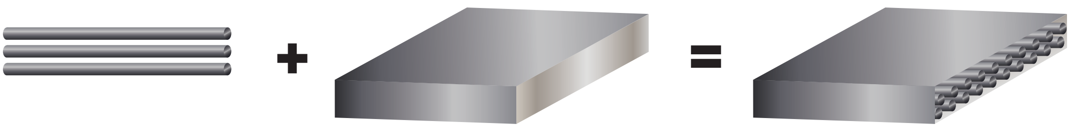
Composites vs. Advanced Composites

Composites are comprised of two or more materials working together, where each constituent material retains its unique identity within the composite and contributes its own structural properties, yet upon combination the resulting material has superior properties to those of its constituents. A good example of an everyday composite material is concrete. Concrete is made with select amounts of sand, aggregate, and perhaps even glass fiber mixed with cement to bind it together. If the concrete were broken open, the individual constituents would be visible. The type and quantities of these individual constituents can also be adjusted to give the resulting concrete different properties depending on the application.

This textbook is focused on composite laminates, which combine fibers and a matrix material that binds the fibers together. There are many different types of composite materials in use today. One example is fiber-reinforced plastic (FRP) composites made with short glass fibers in a polymer resin or plastic matrix. These materials are used in bath tubs, showers, pools, doors, car fenders, and a variety of construction materials including wall panels, corrugated sheet, profiles, and skylights. (Figure 1-1)

FIGURE 1-1. Fiber-reinforced composite



Fibers
- Tensile strength
- Flexural stiffness
- Somewhat brittle

Matrix
- Compressive strength
- Interlaminar shear
- Controls shape
- Low density

Composite
- Increased strength
- Increased stiffness
- Increased toughness
- Lightweight

Highly loaded composite structures typically use continuous or long-fiber reinforcement that transfers load along bundles or layers (**plies**) of fibers arranged to run the length and width of the structure, much like the layers in a sheet of plywood. This type of composite laminate is used in the manufacture of boats, bridges, snowboards, bicycle frames, race cars, aircraft and spacecraft structures, to mention a few.

ADVANCED COMPOSITES

"Advanced composites" are generally considered to be those that use advanced reinforcements such as carbon, aramid and S2 glass fibers that exhibit high strength-to-weight ratios.[1] They are typically more expensive, with more precisely tailored properties to achieve a specific objective.

Fiberglass vs. Advanced Composites

Some composites are generally referred to as "fiberglass" due to their use of randomly-oriented, chopped glass fiber (E-glass) and polyester resin, whereas most aerospace structural parts are made using precisely-laid plies of carbon fiber/epoxy **prepreg,** an example of advanced composites. (Figure 1-2)

Examples of Typical Applications

Large components of commercial airliners—such as the vertical and horizontal tail plane (stabilizer) on the Airbus A320, A330/340, A380 and Boeing 777, the wing, center wing box and fuselage for the Boeing 787 Dreamliner and Airbus A350, and various structures on many smaller craft such as the wings for the Bombardier C Series airliners. (Figure 1-3)

Large primary structures on military aircraft—such as the wing and cargo doors for the Airbus A400M transport, fuselage/wing for the B-2 Spirit Stealth Bomber, rotor blades and aft fuselage for the V-22 Osprey tilt-rotor, as well as the most of the fuselage and wings for the F-22 Raptor and F-35 Joint Strike Fighter. (Figure 1-4)

FIGURE 1-2. Fiberglass vs. advanced composites

[a] To fabricate an aerospace structural component, technicians carefully lay down each ply of carbon-fiber prepreg prior to vacuum bagging and autoclave cure. Green "templates of light" are accurately projected from a 3D laser projector to ensure precise positioning of the ply. *(Photo courtesy of Assembly Guidance)*

[b] Chopped fiberglass and resin are sprayed onto a gel-coated mold to form the outer shell of a Class 8 truck hood. However, this is a more advanced and higher performance example of spray-up fiberglass because the shell is cured in an oven at 130°F and then reinforced with structural members made using RTM, which are secondarily bonded in-place using methacrylate adhesive. *(Photo courtesy of Marine Plastics Ltd.)*

1 ASM Handbook Volume 21, *Composites* (pg. 1113) defines "advanced composites" as: "Composite materials that are reinforced with continuous fibers having a modulus higher than that of fiberglass fibers. The term includes metal matrix and ceramic matrix composites, as well as carbon-carbon composites." Material Park, Ohio; ASM International, 2001.

FIGURE 1-3. A350 forward fuselage [a]; prototype center wing box for future A320-type aircraft [b]; A350 lower wing cover [c]. *(Photos courtesy of Airbus)*

Bottom diagram: Boeing 787 Dreamliner composite components.

FIGURE 1-4. The F-35 Lighting II Joint Strike Fighter features vertical tail feathers and horizontal stabilators made from carbon fiber-reinforced bismaleimide composite. *(Photo courtesy of Lockheed Martin)*

Many other components on modern airliners—such as radomes, control surfaces, spoilers, landing gear doors, wing-to-body fairings, passenger and cargo doors, trailing edges, wingtips and interiors. (Figure 1-5)

Large marine vessels and structures including hulls, decks and superstructure of military and commercial vessels, as well as composite masts (one of the largest carbon fiber structures in the world is the *M5* sailing yacht's 290-foot mast), wing masts and foils, rigging, propellers and propeller shafts. (Figure 1-6)

Primary components on helicopters including rotor blades and rotor hubs have been made from carbon fiber (CF) and glass epoxy composites since the 1980s. Composites can make up 50 to 80% of a rotorcraft's airframe by weight, including radomes, tail cones and large structural assemblies. (Figure 1-7) For example, Bell Helicopter Textron's 429 corporate/EMS/utility helicopter features composite structural sidebody panels, floor panels, bulkheads, nose skins, shroud, doors, fairings, cowlings and stabilizers, most made from CF/epoxy.

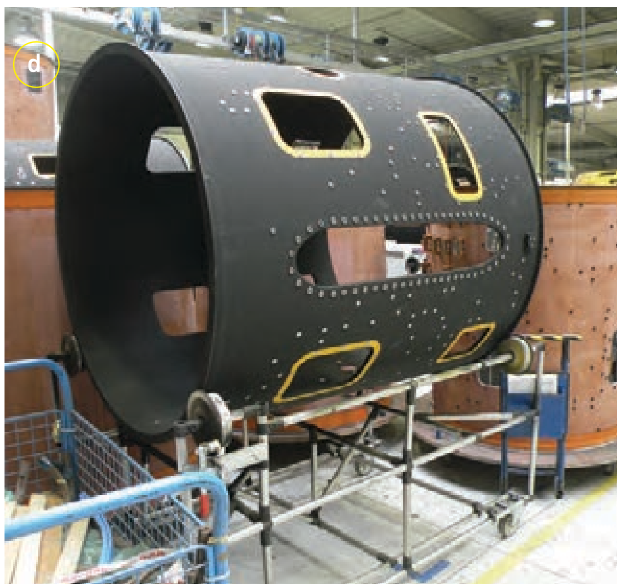


FIGURE 1-5. Airliner components

[a] J-nose thermoplastic composite leading edge for the Airbus A380 made by Stork Fokker. Note the stamped thermoplastic stiffeners, which are attached using resistance welding.
(Photo courtesy of Stork Fokker)

[b, c, d] FACC is a leading Tier 1 supplier with composite structures on every commercial aircraft in production, including carbon fiber/epoxy flaps for the Airbus A321 [b], translating sleeves for the Boeing 787 [d], and bypass ducts for Rolls-Royce aircraft engines [c]
(Photos upper right and bottom, courtesy of FACC)

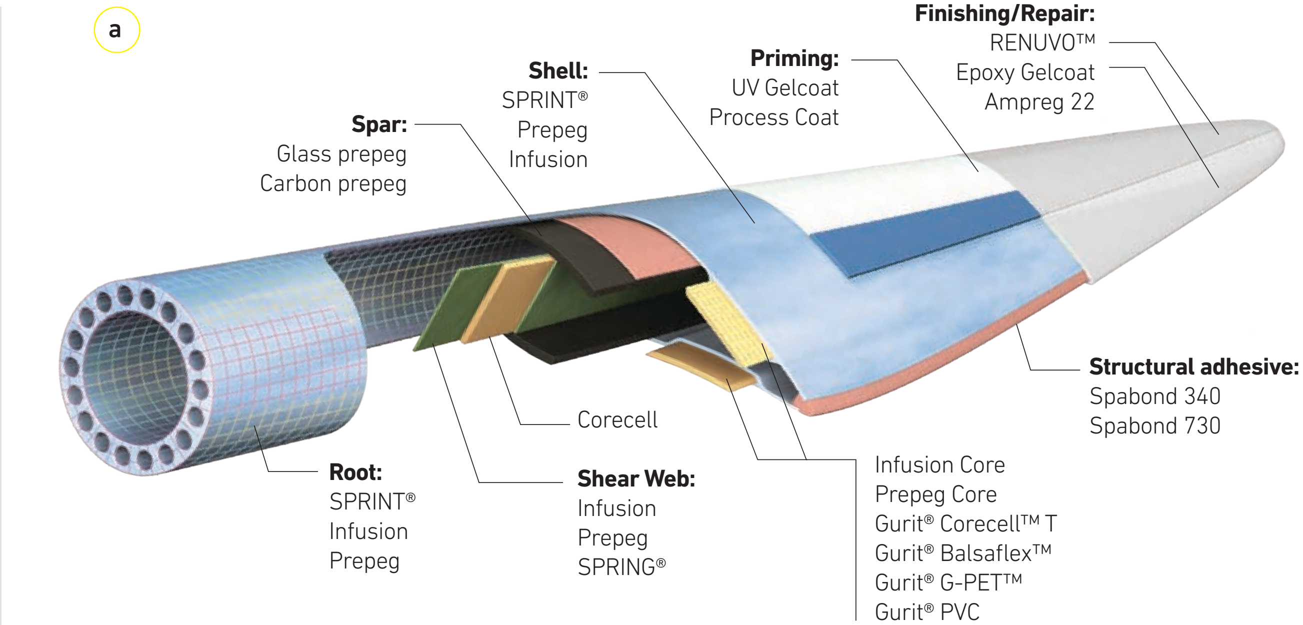
FIGURE 1-6. Marine structures

Left to right, top to bottom: The *M5* (previously the *Mirabella V*) is the world's largest composite ship. *(Photo courtesy of Select Charter Services)*

- The Visby class of corvettes is built using carbon-fiber-reinforced composite sandwich construction. *(Photo courtesy of Kockums AB)*
- Placid Boatworks' 3.6m long, 8-kg *Spitfire Ultra* canoe uses carbon fiber biaxial (±45°) and quasi-isotropic (0°/+60°/-60°) braided fabrics in the hull and biaxial braided carbon and aramid sleeving wrapped around Divinycell foam in the gunwales. *(Photo courtesy of Placid Boatworks)*
- The lightweight composite construction for CMN Group's 43.6m *Ocean Eagle 43* Ocean Patrol Vessel (OPV) was built by H2X using glass fiber/epoxy/foam core sandwich and resin infusion. *(Photo courtesy of H2X)*
- The ECsix composite rigging on this sailing yacht is made from a bundle of 1-mm pultruded carbon fiber/epoxy rods encased in an abrasion-resistant braided synthetic fiber jacket. Able to cut rigging weight by 70%, ECsix has been used on over 500 yachts, sailing more than 1 million miles without a single failure. *(Photo courtesy of Composite Rigging/Southern Spars)*
- The 48m Palmer Johnson SuperSport yacht features all-carbon fiber composite construction made using vacuum infusion. *(Photo courtesy of Brødrene Aa)*

FIGURE 1-7. Airbus helicopter components

Airbus Helicopter's H160 twin-engine medium helicopter features an all-composite airframe, new composite Biplane Stabilizer™, Blue-Edge® composite main rotor blades with double-swept tips, a CF/PEKK thermoplastic composite rotor hub and a double-canted tail incorporating the largest-ever composite Fenestron® shrouded tail rotor *(inset)*. *(Photos courtesy of Airbus Helicopter)*



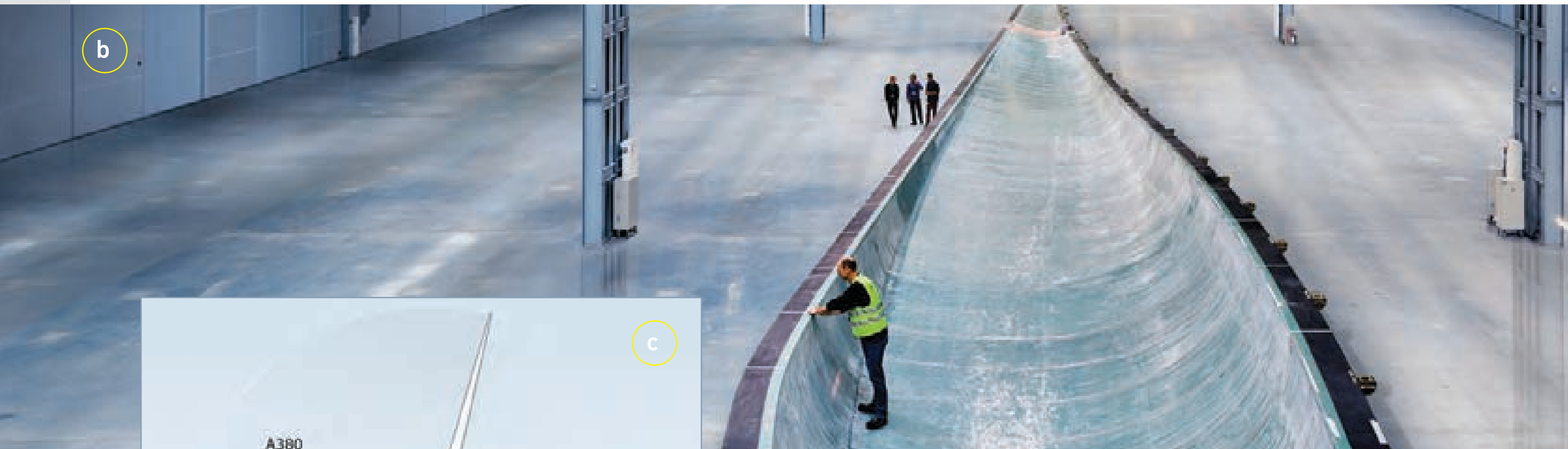


FIGURE 1-8. Wind turbine blades

[a] The various composite materials used in wind turbine blades. *(Diagram courtesy of Gurit)*

[b & c] Siemens 6MW offshore wind turbine featuring a 154m diameter rotor uses its 75m long glass fiber, epoxy resin and balsa core blades made using its IntegralBlade technology. *(Courtesy of Siemens Renewable Energy)*

[d] SSP Technology, in partnership with Samsung Heavy Industries, built the 83.5m blade for SHI's prototype 7MW offshore wind turbine. *(Photo courtesy SSP Technology)*

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Matrix Technology

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45 Prepregs

Matrix Systems Overview

A composite matrix acts to bond and/or encapsulate the fiber reinforcement, enabling the transfer of loads from fiber to fiber. It also moderately protects the fibers from degradation due to environmental effects, including moisture, ultraviolet (UV) radiation, chemical attack, abrasion and impacts. Matrix materials can be molded, cast, or formed to shape. Types include: polymeric (plastic), metallic, and ceramic. Matrix-dominated structural properties include compression, interlaminar shear, and ultimate service temperature.

Selection of a matrix material has a major influence on the shear properties of a composite laminate, including interlaminar shear and in-plane shear. The interlaminar shear strength is important for structures functioning under bending loads, whereas the in-plane shear strength is important under torsion loads. The matrix also provides resistance to fiber buckling in a laminate under compression loads and therefore is considered a major factor in the compressive strength of a composite.

Thermoset resins are primarily used for highly loaded structures because of their high strength and relative ease of processing. Thermoplastic resins are utilized where toughness or impact resistance is desired, or when high-volume production dictates the need for a fast processing material. Metallic and ceramic matrices such as titanium and carbon are primarily considered for very high temperature applications (> 650°F/343°C).

Thermosets

With thermoset resins, the molecules are chemically reacted and joined together by **cross-linking**, forming a rigid, three-dimensional network structure. Once these cross-links are formed during cure, the molecules become locked-in and cannot be melted or reshaped again by the application of heat and pressure. However, when a thermoset has an exceptionally low number of cross-links, it may still be possible to soften it at elevated temperatures. (*See also* "Thermoset – Thermoplastics," Page 36.)

Thermoset resins typically require time to fully react or "cure" at temperatures ranging from room temperature to upwards of 650°F (343°C), depending on the chemistry. Examples of thermoset matrix materials include as follows: polyester, vinyl ester, polyurethane, epoxy, phenolic, benzoxazine, cyanate ester, bismaleimide, and polyimide resins.

Many thermoset resins bond well to fibers and to other materials; for this reason, many thermoset resins are also used as structural adhesives, paints, and coatings. Structural properties for some common thermoset matrix systems at 77°F (25°C) are shown in Tables 2.1 and 2.2.

TABLE 2.1 Typical Thermoset Matrix Systems for Composites

Matrix System	Tensile Strength Ksi (MPa)	Tensile Modulus Msi (GPa)	% Elongation to Failure	*Cost
Polyester (UP)	3–11 (20.7–75.8)	0.41–.0.50 (2.8–3.4)	1-5	Low
Vinyl Ester (VE)	10–12 (68.9–82.7)	0.49–0.56 (3.4–3.9)	3-12	Low-Med
Polyurethane (PU)	9 – 15 (62.1–103.4)	0.35–0.48 (2.4- 3.3)	6-14	Low-Med
Epoxy (EP)	7–13 (48.3–89.6)	0.39–0.54 (2.7–3.7)	2-9	Medium
Phenolic (PF)	7–9 (48.2–62.1)	0.43 - 0.60 (2.9 - 4.1)	1-2	Low-Med
Benzoxazine (BZ)	7 – 16 (48.3 - 110.3)	0.49 - 0.81 (3.4 - 5.6)	1-5	Medium
Bismaleimide (BMI)	7–13 (48.3–89.6)	0.48–0.62 (3.3–4.3)	1-3	High
Cyanate Ester (CE)	7–13 (48.3–89.6)	0.40 - 0.50 (2.8–3.4)	2-4	Very High
Polyimide (PI)	5–17 (34.5–117.2)	0.20–0.70 (1.4–4.8)	1-4	Very High

*Relative cost comparison to polyester.

TABLE 2.2 Initial Cure Temperature vs. Service Temperature for Thermosets

Matrix System	Initial Cure Temperature	Maximum Service Temperature*
Polyester (UP)	R/T - 250°F ▪ R/T - 121°C	135° - 285°F ▪ 58° - 140°C
Vinyl Ester (VE)	R/T - 200°F ▪ R/T - 93°C	120° - 320°F ▪ 49° - 160°C
Polyurethane (PU)	R/T - 390°F ▪ R/T - 200°C	140° - 355°F ▪ 60° - 180°C
Epoxy (EP)	R/T - 350°F ▪ R/T - 177°C	120° - 360°F ▪ 49° - 182°C
Phenolic (PF)	140°F– 250°C ▪ 60°– 121°C	300°–500°F ▪ 148°–260°C
Benzoxazine (BZ)	300°– 475°F ▪ 148°– 246°C	250°–465°F ▪ 121°–240°C
Bismaleimide (BMI)	375°– 550°F ▪ 190°–288°C	400°–540°F ▪ 204°–282°C
Cyanate Ester (CE)	250°– 350°F ▪ 121°–177°C	200°–600°F ▪ 93°–316°C
Polyimide (PI)	640°– 750°F ▪ 316°–399°C	500°–600°F ▪ 260°–316°C

*Note: The operational service temperature of any thermoset resin will largely depend upon the ultimate Glass Transition Temperature (T_g) of a specified resin chemistry, as well as the cure/post-cure time and temperature that the resin has seen during processing.

GLASS TRANSITION TEMPERATURE (T_g) AND SERVICE TEMPERATURE

The glass transition temperature is the temperature at which increased molecular mobility results in significant changes in the properties of a solid polymeric resin or fiber. In this case, the upper temperature "glass transition" (or T_g, which is pronounced "t-sub-g") refers to the transition in behavior from rigid to "rubbery."

This can be thought of as the temperature above which the mechanical properties of a cured thermoset polymer are diminished. While it is not necessarily harmful for a structure to see temperatures moderately above the T_g, the structure should always be supported above this temperature to prevent laminate distortion.

When curing a thermoset polymer, the "rate of cure" (or rate of chemical reaction) is accomplished faster above the glass transition temperature than below it. Therefore, final cure temperatures are typically engineered to be as near as practical to the final desired T_g in order to minimize the cure time.

During processing it is important to differentiate between the "state-of-cure" (percent of chemical reaction completed) and the glass transition temperature. A common misconception is that a selected cure temperature alone determines the final glass transition temperature of the polymer. In the case of a *partially reacted* thermoset polymer, it will continue to "cure" over time at a given temperature until it is completely reacted, which can actually elevate the T_g. For example, a thermoset polymer that is heated to 350°F (177°C) may initially have a T_g at or below this temperature. However, after several hours at this temperature, it may ultimately attain a much higher T_g. Therefore, just attaining a specific cure temperature for a limited time will not necessarily produce the desired ultimate glass transition temperature of the polymer.

A similar concern is that a material may appear to be properly cured because it has been to a specified temperature and it exhibits the required strength and stiffness properties when tested at room temperature, but it may have not yet achieved a full state of cure nor the ultimate T_g required to carry design loads under "hot/wet" service conditions.

Alternatively, a *fully reacted* polymer with an ultimate T_g of, for example, 275°F (135°C), will not necessarily increase regardless of added temperature or time at that temperature (*see* Figure 2-1 on the next page).

After initially processing a polymer to a full state of cure, the resulting T_g is typically referred to as the "dry" T_g. Ingress of moisture or other fluids into the structure when exposed to a hot-wet service environment reduces the T_g. This is often referred to as the "wet" T_g and it is considered to be the upper temperature limitation of the polymer. As a general rule, the maximum designed service temperature limit of a composite structure is often well below this threshold.

The T_g of a given **neat-resin** or composite sample can be established using one of the following methods of Thermal Analysis (TA): Thermomechanical Analysis (TMA), Dynamic Mechanical Analysis (DMA), and Differential Scanning Calorimetry (DSC).

HEAT DEFLECTION TEMPERATURE, OR HEAT DISTORTION TEMPERATURE (HDT)

Many resin manufacturers will cite the heat deflection temperature (HDT) as a measure of the upper temperature capability of a resin in lieu of the T_g. The HDT is a simpler concept to understand than that of T_g outside of the scientific laboratory, and is used by many part manufacturers as a reliable method of thermal analysis. Both methods are used to define the upper temperature limitations of composite materials within industry.

Manufacture

Textile-grade glass fibers are made from silica (SiO_2) sand which melts at 1,720°C/3,128°F. Though made from the same basic element as quartz, glass is amorphous (random atomic structure) and contains 80% or less SiO_2, while quartz is crystalline (rigid, highly-ordered atomic structure) and is 99% or more SiO_2. Molten at roughly 1,700°C/3,092°F, SiO_2 will not form an ordered, crystalline structure if cooled quickly, but will instead remain amorphous—i.e., glass. Although a viable commercial glass fiber can be made from silica alone, other ingredients are added to reduce the working temperature and impart other properties useful in specific applications. (*See* Table 3.2, "Comparison of E and S-2 glass fibers.")

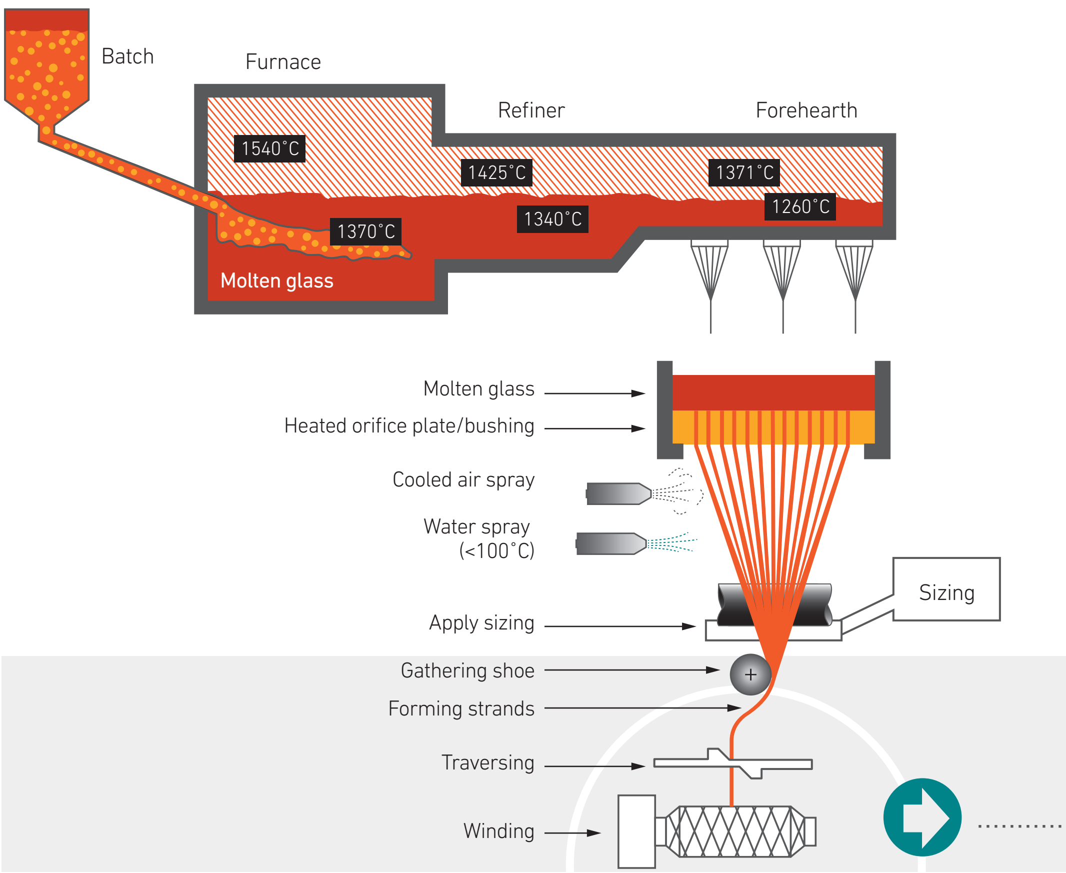
For example, E-glass, originally aimed at electrical applications, with a composition including SiO_2, Al_2O_3 (aluminum oxide or alumina), CaO (calcium oxide or lime), and MgO (magnesium oxide or magnesia), was developed as a more alkali-resistant alternative to the original soda lime

TABLE 3.2 Comparison of E and S-2 glass fibers

Composition	E-glass	S-2 Glass®*
Silicon Dioxide	52–56%	64–66%
Calcium Oxide	16–25%	
Aluminum Oxide	12–16%	24–26%
Boron Oxide	8–13%	
Sodium & Potassium Oxide	0–1%	
Magnesium Oxide	0–6%	9–11%

*S-2 GLASS® is a registered trademark of AGY.

FIGURE 3-4. Glass fiber manufacturing process. *(continued at right)*



glass. S-glass fibers (i.e., "S" for high strength) contain higher percentages of SiO_2 for applications in which tensile strength is the most important property.

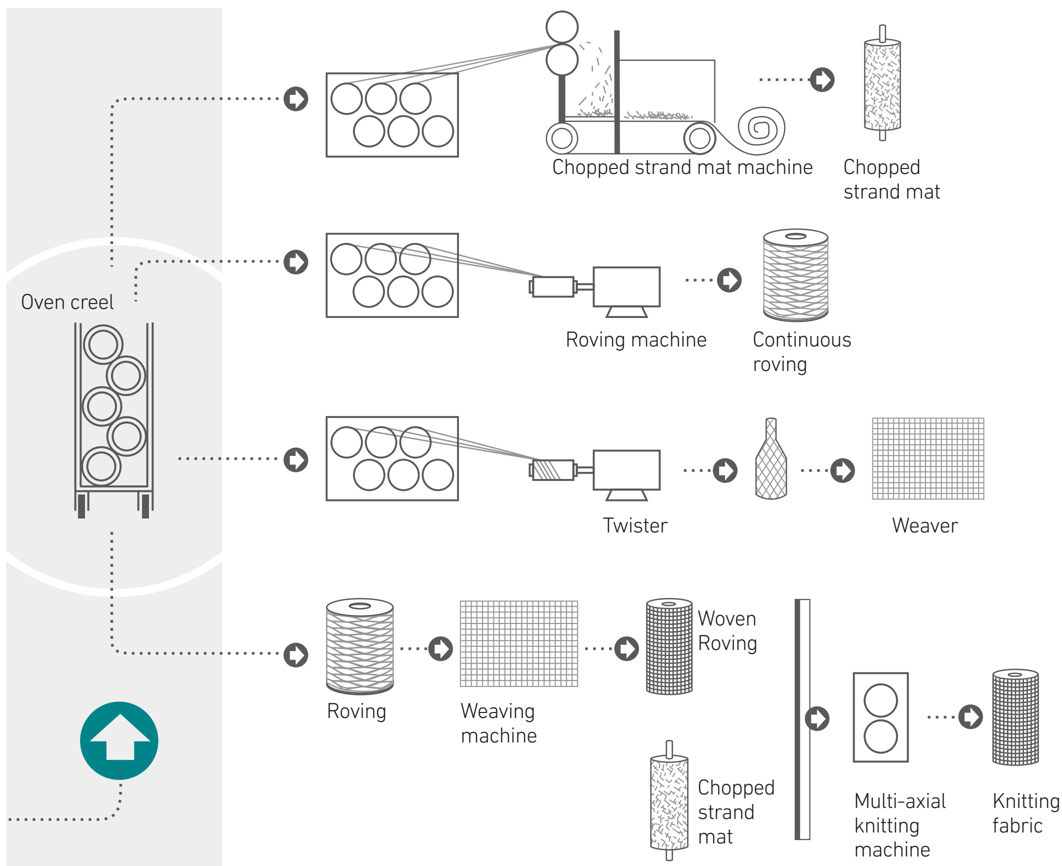
Glass fiber manufacturing begins by carefully weighing exact quantities and thoroughly mixing (batching) the component ingredients. The batch is then melted in a high temperature (~1,400°C/2,552°F) natural gas-fired furnace. Beneath the furnace, a series of four to seven bushings are used to extrude the molten glass into fibers. Each bushing contains from 200 to as many as 8,000 very fine orifices. As the extruded streams of molten glass emerge from the bushing orifices, a high-speed winder catches them and, because it revolves very fast (~2 miles/3 km per minute—which is much faster than the speed the molten glass exits the bushings), tension is applied and this draws the glass streams into thin filaments (i.e., fibrous elements ranging from 4–34 μm in diameter, or 1/10 that of a human hair). (Figure 3-4)

Fiber Diameter and Yield

The bushings' orifice or nozzle diameter determines the diameter of the glass filament; nozzle quantity equals the number of ends. A 4,000-nozzle bushing may be used to produce a single roving product with 4,000 ends, or the process can be configured to make four rovings with 1,000 ends each. The bushing also controls the fiber yield or yards of fiber per pound of glass.

The metric unit, tex, measures fiber linear density: 1 tex = 1 g/km; while yield is the inverse, yd/lb. A fiber with a yield of 1,800 yd/lb (275 tex) would have a smaller diameter to a 56 yd/lb (8,890 tex) fiber, and an 800-nozzle bushing produces a smaller yield than a 4,000-nozzle bushing.

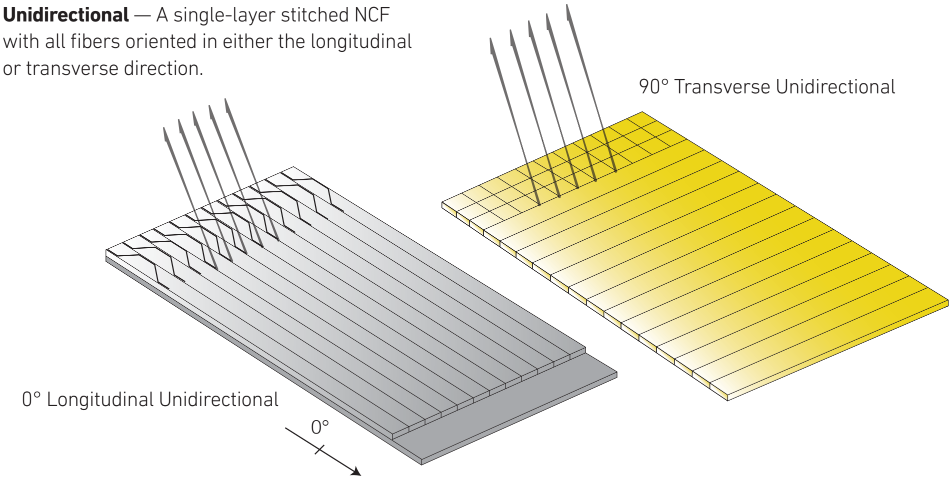
FIGURE 3-4. *Continued.*

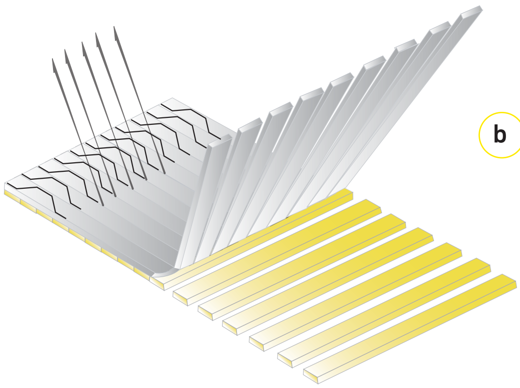


Multiaxial Fabric Types

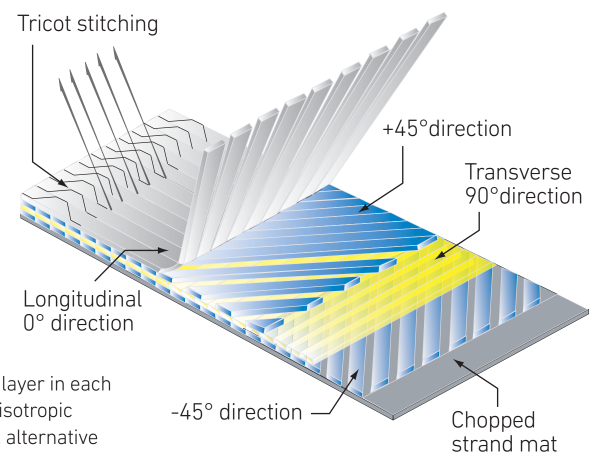
Multiaxial fabrics were first produced using the common angles that comprise a quasi-isotropic stacking sequence, namely 0°, 90°, +45°, -45° or some combination of these. These are still the most common NCF configurations, but the angles possible have since changed. *See* "Thin-ply Bi-angle Fabrics" on Page 104.

a **Unidirectional** — A single-layer stitched NCF with all fibers oriented in either the longitudinal or transverse direction.

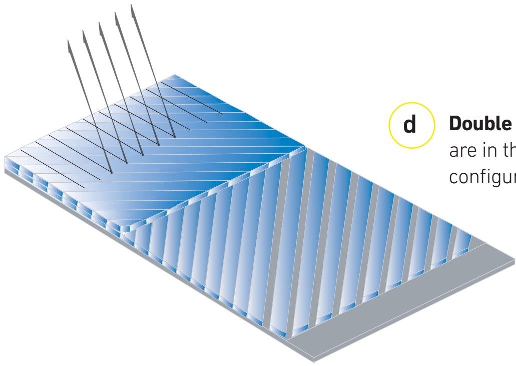




b **Biaxial** — A two-layer stitched NCF. The most common configuration is to have one layer in the 0° direction and one layer in the 90° direction. The second most common form is a double bias.

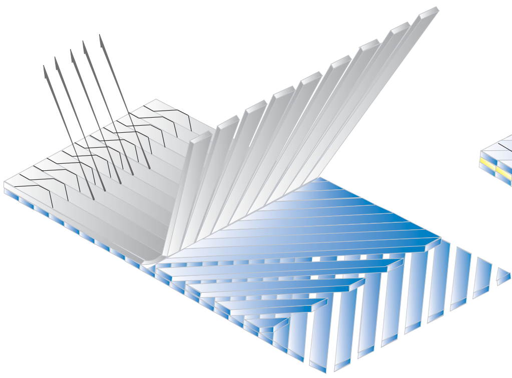


c **Quadraxial** — A four-layer NCF with one layer in each of the four primary directions of a quasi-isotropic layup: 0°/+45°/90°/-45°. Less common, alternative configurations are also possible.

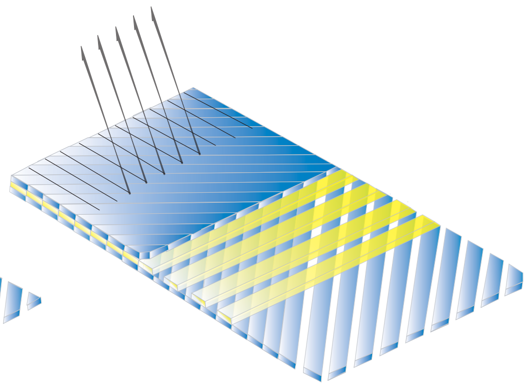


d **Double bias** — A biaxial stitched NCF where the layers are in the +45° and -45° direction. (Less common configurations could include +60°/-60°, +30°/-30°, etc.)

e **Triaxial** — A three-layer stitched NCF that can either be longitudinal or transverse. The most common configuration includes 0° and ±45°, but others are possible.



Longitudinal triaxial: one layer in the 0° direction and the other two layers in the +45° and -45°.



Transverse triaxial: one layer in the 90° direction and the other two layers in the +45° and -45°.

All diagrams of stitched multiaxial fabrics are courtesy of Vectorply Corporation.

Numbering System

The numbering system commonly used with these fabrics was developed by Knytex when it introduced what it called "knit multiaxials" in 1975. Even if a fabric is named with an unrelated product number by the manufacturer, end-users may commonly still refer to it as an 1808 or 2408, for example.

First 2 Numbers—the weight of the fabric in oz/yd^2.
Second 2 Numbers—the weight of any chopped strand mat (CSM) in oz/ft^2 x 10.

TABLE 3.21 Common Stitched Multiaxial Glass Fabrics

Product	1808	2400	2408	2415	3208	3610	5600
Fabric Weight (oz/yd^2)	18	24	24	24	32	36	56
Mat Weight (oz/ft^2)	.8	-	.8	1.5	.8	1.0	-

Note: Vectorply has a 10800 product with a fabric weighing 108 oz/yd^2 and no mat.

TABLE 8.7 Advantages and Disadvantages of Injection Molding

Advantages	Disadvantages
• Ability to produce millions of parts quickly • Low scrap rates vs. machining from blocks of material (but not as low as 3D printing) • Very repeatable, high part reliability throughout production volume • Very good at producing small parts with complex geometries • Offers the ability to integrate many parts into a single, molded piece	• Significant expense and lead time to develop tooling (though this is improving by using additive manufacturing) • Can be difficult to make changes • Significant investment in equipment (though this is also changing with ability to lease machines) • Not as good at producing large parts with high wall thickness and undercuts

Injection molding compounds are typically supplied as pre-compounded pellets, which are melted and then injected within the molding machine. Because some polymers absorb water from the atmosphere, proper material storage, handling, drying and machine feed conditions must be maintained in order to achieve consistent, high-quality injection molded parts.

Pellets are loaded into the hopper, which feeds them into the heated barrel of the machine where they are melted. A reciprocating screw continues to feed and mix the proper amount of material. The screw ram-injects a shot of the material into the mold cavity where it cools and conforms to the mold shape. After cooling, the finished part is ejected from the mold and the cycle is completed. Injection molding cycles are normally less than 60 seconds long, with cooling comprising more than 50% of the total cycle time. (Figure 8-42)

Examples of applications include injection-molded wood plastic composite cases, gears, car interiors, toys and consumer goods (*see* Figure 3-15); chopped glass fiber reinforced nylon and polypropylene parts such as washing machine tubs and under-hood car parts (*see* Figure 3-19); and nylon reinforced with chopped glass, carbon or natural fibers for automotive parts used in doors, instrument panels, front end carriers and liftgate assemblies.

LONG FIBER THERMOPLASTIC (LFT) AND DLFT

LFT materials typically use fibers that are 0.5 – 1.0 inch (13 – 25 mm) in length. However, for both short fiber and LFT compounds, the fibers will be sheared during mixing and injection, reducing length to roughly 1 – 3 mm for LFT compared to approximately 0.3 mm for short-fiber compounds.

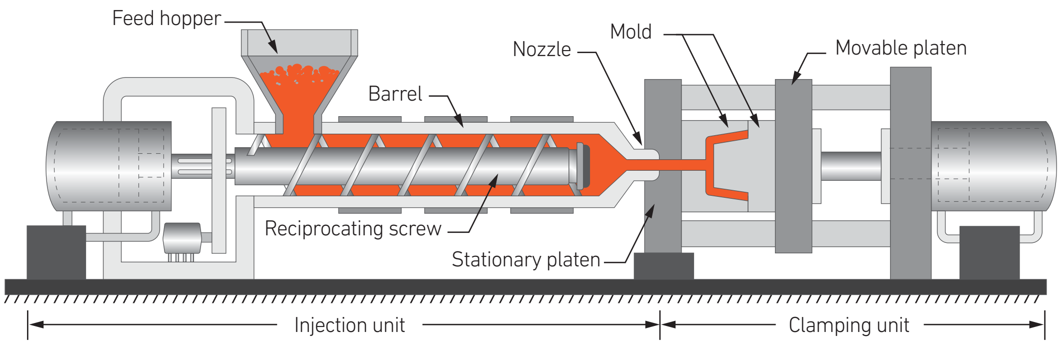


FIGURE 8-42. Injection molding machine.

LFT offers higher mechanical properties than standard short-fiber compounds, including tensile and impact strength, dimensional stability and thermal stability. LFT pellets are made by pultrusion and most commonly use glass or carbon fiber. Hybrid pellets combining glass and carbon fiber have been made as well. Matrix polymers include PA, PA6, PA66, PBT, PC, PET, PP, PPS and TPU.

The process for *direct* long fiber thermoplastic (D-LFT or LFT-D) directly chops fiber and mixes it with resin at the injection machine—i.e., the reinforced thermoplastic is directly compounded and then molded in one operation. D-LFT is described as a cross between injection molding and compression molding. Initially, the process evolved out of reinforced injection molding, and thus comprised feeding the mixed material through a transition tube into an injection molding press screw, like that shown in Figure 8-42. However, increasing fiber length began to reach the limits of injection molding, clogging the equipment. Therefore at the higher end of fiber length, D-LFT consists of compounding the material inline and then placing it as a charge into a compression molding tool and press. (Figure 8-43)

With D-LFT, chopped fiber lengths are extended to as high as 50 mm. PP, PET and PBT are listed as the most common thermoplastic matrix materials and though glass fiber has historically been the most common reinforcement, applications using carbon fiber have been increasing.

One advantage of D-LFT is that molders have more control over materials versus using pre-compounded pellets, including the ability to choose precise polymer and fiber types, as well as fiber length and fiber content, with the latter controlled to a variation of less than ±2% by weight, according to some D-LFT equipment suppliers. Cost savings are also claimed as a key benefit, while properties are equal to or greater than LFT pellets.

DLF AND REGRINDING WASTE

DLF® is an acronym used by Greene, Tweed for its "discontinuous long fiber" technology. However, it does not use injection molding but instead compression molding (*see* Chapter 7) of Xycomp® carbon fiber-reinforced composites that may use PEI, PPS, PEEK or PEKK thermoplastic polymer as a matrix. DLF materials may be formed by chopping prepreg tape. In this way, they are more similar to a long fiber compression molding materials, for example SEREEBO™ (20-mm-long carbon fiber in PA6 matrix) developed by Teijin. While Sereebo™ was developed for automotive applications, DLF is targeted for aerospace and replaces metal in brackets and also in oil and gas tubulars and fittings, cutting weight up to 60% and integrating multiple parts into a single component.

One part of the Sereebo™ process is common to D-LFT long fiber injection molding processing described above: regrinding of part production scrap and mixing with virgin material in a screw extruder. This can be seen in the use of Sereebo™ to mold the 2019 GM

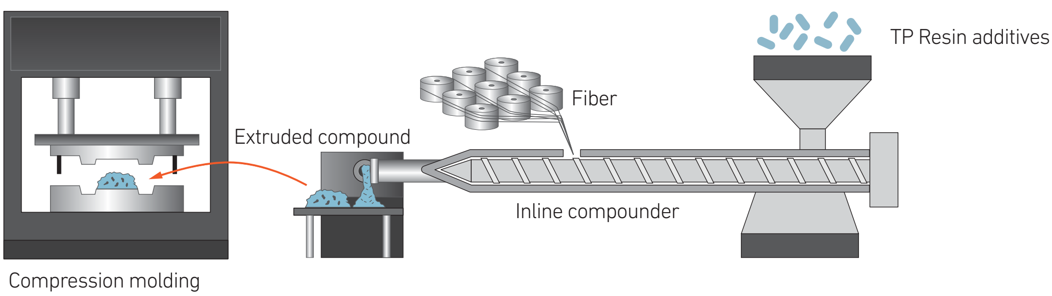


FIGURE 8-43. D-LFT process using compression molding. In this diagram, thermoplastic pellets are melted and mixed inline with chopped fiber and then extruded as a charge, which is placed into a compression molding tool and press.