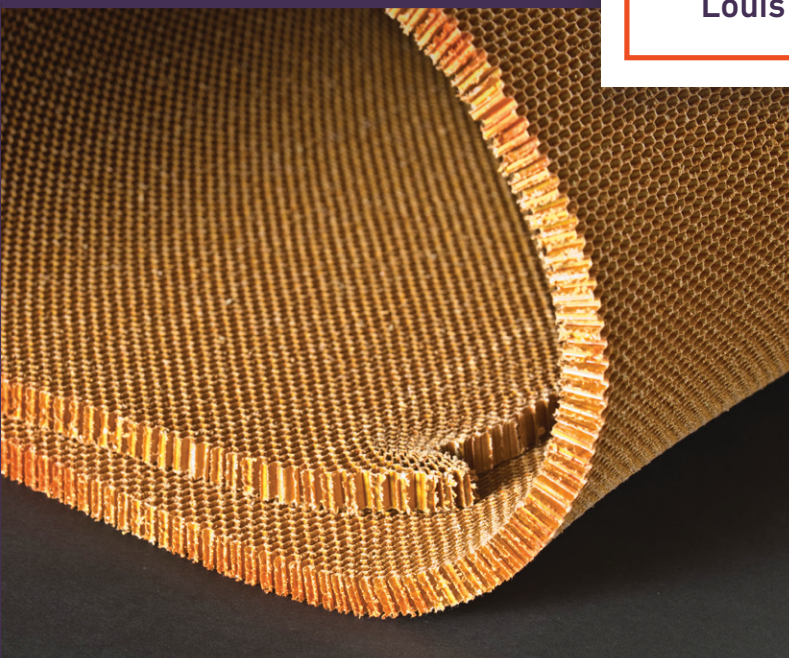




Essentials of Advanced Composite Fabrication and Repair

THIRD EDITION

Louis C. Dorworth Ginger L. Gardiner



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Third Edition
by Louis C. Dorworth and Ginger L. Gardiner

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See the Reader Resources at asa2fly.com/composite for additional information and updates related to this book.

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Preface

Updated from the second edition, this third edition of ***Essentials of Advanced Composite Fabrication and Repair*** covers a wider range of contemporary technical material and is designed to function as a textbook both for Abaris Training and for other technical schools teaching composites. It is an “essential” resource for everyone, 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. Training Academy and other pioneer thought 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 quickly became useful 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 the second 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. The second edition was published in 2019, and by 2023 it became clear that a third edition of the textbook was needed to further update the industry.

Like the second edition, this book starts with an introduction to composites and then takes a deep dive into the constituent materials such as fibers, matrix resins, nanocomposites, core materials, and curing or processing them. This is followed by chapters that cover basic design considerations, molding methods and practices, tooling, testing, bonding, machining, drilling, repair, and much more. In addition, online Reader Resources on the publisher’s website at asa2fly.com/composite provide additional information and future updates relating to this book’s content.

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 in the workplace, on their projects, or to further advance their careers.

About the Authors



LOUIS C. 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. Louis has been involved in the advanced composites industry since 1978, starting in aerospace as a toolmaker and part-time M&P technician at Lear Fan in Reno, Nevada, after which he has continued in the industry

for more than four decades. Louis has been associated with Abaris since its inception in 1983 and began his teaching career at Abaris in 1989.

Louis has been a professional member of the Society for the Advancement of Material & Process Engineering (SAMPE) since 1982 and a senior member of the Society of Manufacturing Engineers (SME) since 1997. He currently serves as an advisor to the SAMPE Technical Excellence Subcommittee for Bonding and Joining, is a member of the Thermoplastics Technical Committee, and is an advisor to 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* magazines in 2006. She has worked as Senior Editor and Senior Technical Editor of the now combined *CompositesWorld* magazine since 2013.

Fiber Reinforcements

CONTENTS

- 61 Introduction and Overview
- 65 Fiber Types and Properties
 - 90 Forms of Reinforcement
- 113 Recycled Fiber

Introduction and Overview

This chapter discusses fiber types, fiber properties, and the different fiber forms that are used in the fabrication of advanced composite structures. Table 3.1 on the next page lists the most common fiber types used in composites. These fibers (e.g., glass, carbon, ceramic and aramid) are detailed in the “Fiber Types and Properties” section beginning on page 65, which examines how they are manufactured, their mechanical properties and how they are prepared for use in composites.

The reinforcement used in composites is also an important consideration. Structural composites typically use a long or continuous form of fiber reinforcement. Non-structural composites may use chopped fibers, which are typically $\frac{1}{4}$ - to 1-inch in length. Fibers that are shorter than this—for example, milled fibers, which are approximately $\frac{1}{32}$ -inch (0.8 mm) in length—have a low aspect ratio (length/diameter) that does not provide much strength. Thus, these are usually not considered as reinforcement, but as fillers offering improved matrix properties such as dimensional stability. We’ll discuss the “Forms of Reinforcement” in more detail starting on page 90. (Figure 3-1)

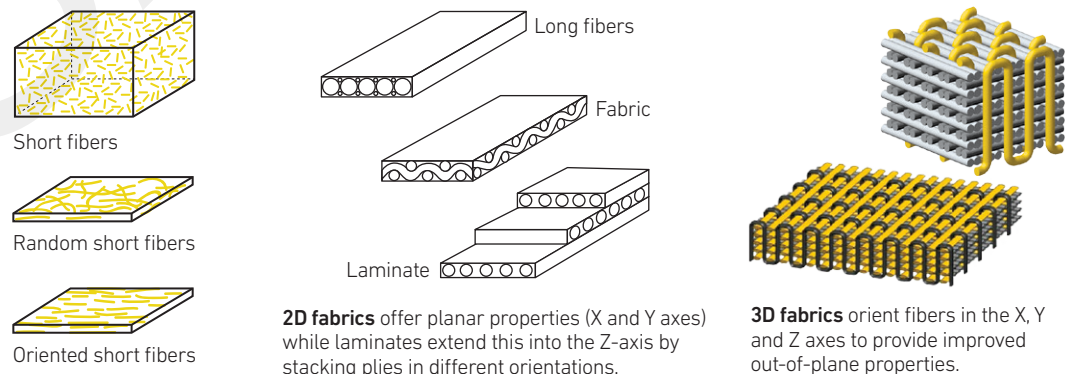


FIGURE 3-1. Forms of reinforcement in composites.

TABLE 3.1 Common Composite Reinforcement Fibers and Properties

FIBER - Type	Density oz/in ³ (g/cm ³)	Tensile strength Ksi (GPa)	Tensile modulus Msi (GPa)	Elongation to break %	Melt or decomposition temp.
CARBON					
- PAN-SM*	1.04 (1.8)	500–700 (3.4–4.8)	32–35 (221–241)	1.5–2.2	6,332°F 3,500°C
- PAN-IM*	1.04 (1.8)	600–1200 (4.1–6.2)	42–47 (290–297)	1.3–2.0	
- PAN-HM*	1.09 (1.9)	600–800 (4.1–5.5)	50–65 (345–448)	0.7–1.0	
- Pitch-LM*	1.09 (1.9)	200–450 (1.4–3.1)	25–35 (172–241)	0.9	
- Pitch-HM*	1.2 (2.0)	275–400 (1.9–2.8)	55–90 (379–621)	0.5	
- Pitch-UHM*	1.24 (2.15)	350 (2.4)	100–140 (690–965)	0.3–0.4	
BASALT					
- Standard	1.56 (2.7)	400–695 (2.8–4.8)	12.5–13.0 (86.2–89.6)	3.0–3.5	2,654°F 1,450°C
GLASS					
- E-glass	1.47 (2.54)	450–551 (3.0–3.8)	11.0–11.7 (75.8–80.7)	4.5–4.9	1,346°F 730°C
- S-2 glass	1.43 (2.48)	635–666 (4.3–4.6)	12.8–13.2 (88.3–91.0)	5.4–5.8	1,562°F 850°C
ARAMID					
- Twaron® 1000	0.84 (1.45)	450 (3.1)	17.6 (121.3)	3.7	850°F 455°C
- Kevlar® 29	0.83 (1.44)	525 (3.6)	12.0 (82.7)	4.0	
- Kevlar® 49	0.83 (1.44)	525 (3.6)	18.9 (130.3)	2.8	
POLYETHYLENE (PE)					
- Spectra® 900	0.56 (0.97)	380 (2.6)	11.5 (79.3)	3.6	302°F 150°C
- Spectra® 1000	0.56 (0.97)	447 (3.1)	14.6 (100.7)	3.3	
- Spectra® 2000	0.56 (0.97)	485 (3.3)	18.0 (124.1)	2.8	
POLYPROPYLENE (PP)					
- PPF	0.55 (0.95)	98.6 (6.8)	0.54 (3.7)	14.0	302°F 150°C
HIGH MOLECULAR WEIGHT POLYPROPYLENE (HMPP)					
- Innegra® S	0.49 (0.84)	96.7 (0.7)	2.5 (14.8)	9.5	302°F 150°C

*Carbon fiber is classified by the stiffness or modulus designation:

SM = Standard Modulus

HM = High Modulus

LM = Low Modulus

UHM = Ultra High Modulus fiber

IM = Intermediate Modulus

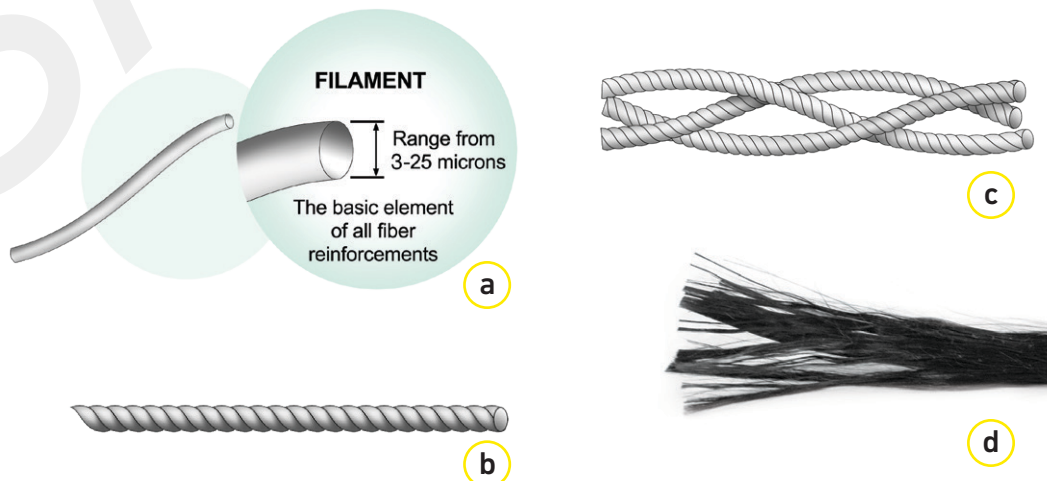
TABLE 3.1 Common Composite Reinforcement Fibers and Properties (*continued*)

FIBER - Type	Density oz/in ³ (g/cm ³)	Tensile strength Ksi (GPa)		Tensile modulus Msi (GPa)	Elongation to break %	Melt or decomposition temp.
POLYPHENYLENE BENZOBISOXAZOLE (PBO)						
- Zylon® AS	0.89 (1.54)	841 (5.8)		26.1 (180.0)	3.5	1,202°F 650°C
- Zylon® HM	0.90 (1.56)	841 (5.8)		39.2 (270.3)	2.5	
OTHER CERAMIC FIBERS						
- Boron	1.49 (2.58)	522 (3.6)		58 (400)	--	3,769°F 2,076°C
- Silicon Carbide (SiC)	1.45–1.73 (2.5–3.0)	360–900 (2.5–6.2)		27–62 (186–428)	0.7–2.2	4,172°F 2,300°C
- Alumina-silica	1.76 (3.05)	250–290 (1.7–2.0)		22–28 (152–193)	0.8–2.0	1,400°F 760°C
- α-alumina	1.97–2.37 (3.4–4.1)	260–510 (1.8–3.5)		38–67 (262–462)	--	1,800°F 982°C
- Quartz	1.25 (2.17)	4	9 (3.4)	3 10.0 (68.9)	5.0	1,920°F 1,050°C

REINFORCEMENT TERMINOLOGY

Figure 3-2 is an illustrated glossary of common terms used in referring to fiber reinforcements.

- [a] Filament**—The very smallest form of the fiber as extruded or spun from the raw materials. Filaments are then combined to make various fiber bundles as described below.
- [b] Strand**—A bundle of filaments twisted into a “mini yarn” for subsequent weaving operations. A term specific to glass fiber, strands of glass can be anywhere from 51 to 1,624 filaments in size.
- [c] Strands to yarn**—Glass yarns are made of a single strand or multiple twisted strands depending on the weight and diameter requirements for subsequent weaving operations and/or processing. (See “Typical Glass Fiber/Fabric Forms and Styles” starting on page 70.)
- [d] Filaments to yarn**—In carbon fiber, common yarn sizes range from 1,000 to 50,000 filaments (1K to 50K). In aramid fiber, yarns can contain from 25 to 5,000 filaments.



(continued)

FIGURE 3-2. Fiber reinforcement terminology.

- [e] **Yarn**—A small, continuous bundle of filaments, tows or combined strands that are gently twisted to enhance bundle integrity. This is important for keeping the yarn intact during subsequent weaving operations.
- [f] **Commingle yarn**—Intimately blending thermoplastic fibers with reinforcing fibers at the filament level. Examples include PEEK, PPS, PE, and PP thermoplastic fibers combined with carbon, glass, aramid, or other reinforcing fibers.
- [g] **Tow**—Basically the same as a yarn, but not twisted, and specific to carbon fiber. The number of filaments comprising a carbon tow is designated in units of 1,000 (e.g., 1K, 12K, 50K). Unidirectional tape is made from multiple tows laid side by side. **Smaller tow sizes** (e.g., 1K, 3K, 6K) are normally used in weaving, winding and braiding applications, and also for very thin unidirectional tapes. **Larger tow sizes** (e.g., 12K, 24K, 50K) are used in unidirectional tapes, stitched multi-axial fabrics, and automated fiber placement processes, and are often spread into thinner spread tows. In general, larger tow sizes are cheaper than smaller tow sizes for the same fiber type (e.g., compare a 50K tow carbon fiber at \$5–10/lb to a 12K at \$15–20/lb).
- [h] **Spread tow**—A tow that has been spread into a wider, thinner form, offering a thinner laminate. The woven fabric form results in straighter fibers and fewer crimps when compared to conventional fabric forms.
- [i] **Roving**—a number of strands, yarns, or tows collected into a parallel bundle with little or no twist. It is a term usually used to describe fiberglass and sometimes aramid reinforcements. **Single-end roving** is made from continuous fiber filament or strand and is typically prescribed for filament winding and pultrusion processes. **Multi-end roving** is made up of long but discontinuous filament bundles that are leafed together into lengthy fiber bundles. Rovings are most commonly used for constructing heavy fabrics called **woven roving** and may also be used for chopper gun/spray-up processes.
- [j] **Tape**—The common name for “unidirectional tape”—all flat parallel tows, available in both dry and prepreg forms. Unidirectional tape is considered to be the most efficient fiber form, as it has no crimps in its construction and each layer is specific to one axis of orientation in layup. Unidirectional tape provides the highest strength-to-weight ratio and has the most efficient on-axis load transfer compared to other forms.
- [k] **Textile**—Item manufactured from natural fiber or man-made filaments, including yarns, tows, threads, roving, cords, ropes, braids, nets and fabrics. Techniques include weaving, knitting, braiding, felting, bonding and tufting.

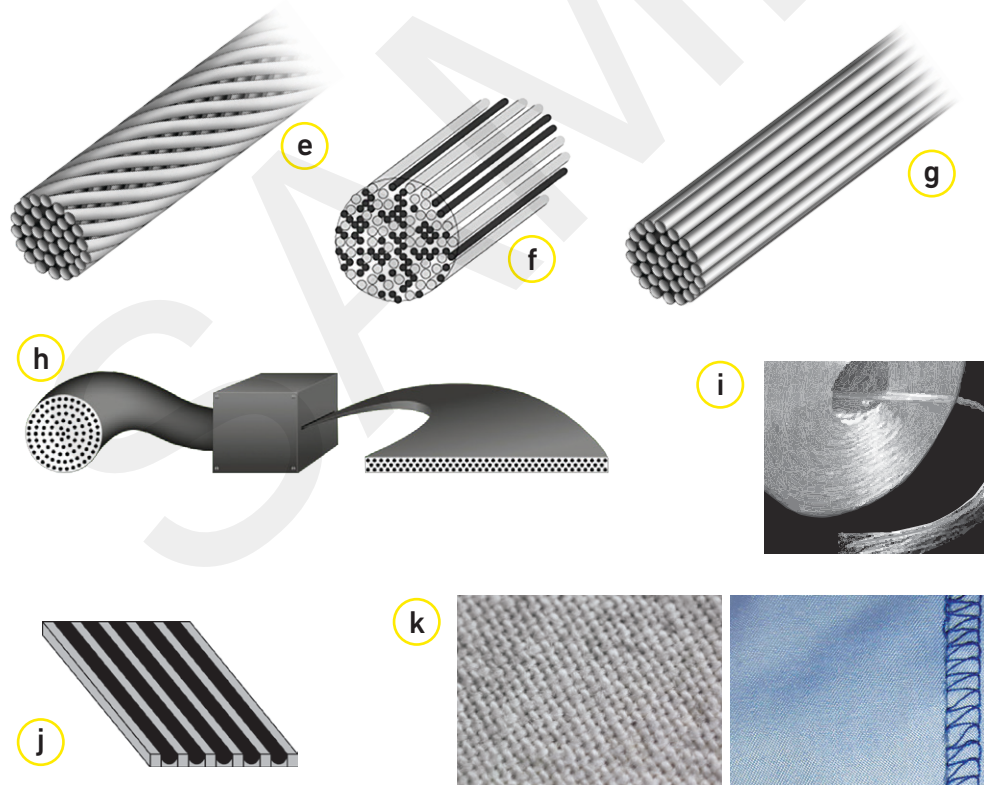
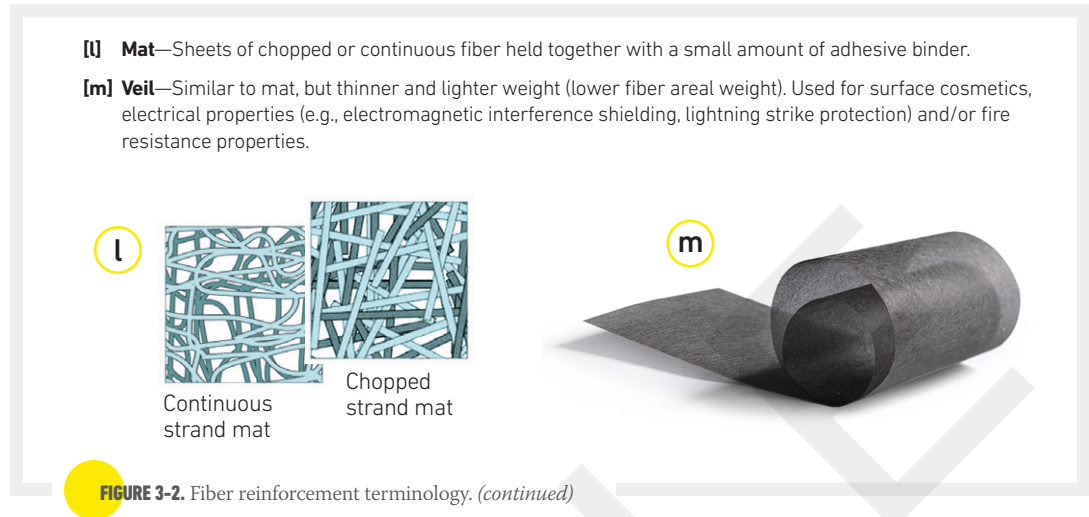


FIGURE 3-2. Fiber reinforcement terminology. (continued)



Fiber Types and Properties

Figure 3-3 lays out the different types of fibers used in composites, under two main categories: natural and synthetic.

GLASS FIBER

NOTE: Text from this section is adapted from “The Making of Glass Fiber” by Ginger Gardiner, Composites Technology Magazine, April 2009; reproduced by permission of Composites Technology Magazine, © 2009 Gardner Publications, Inc., Cincinnati, Ohio

Fiberglass yarns are available in different formulations. “E” glass (electrical grade) is the most common all-purpose glass fiber, while “S-2” (high strength) glass is used for special applications.

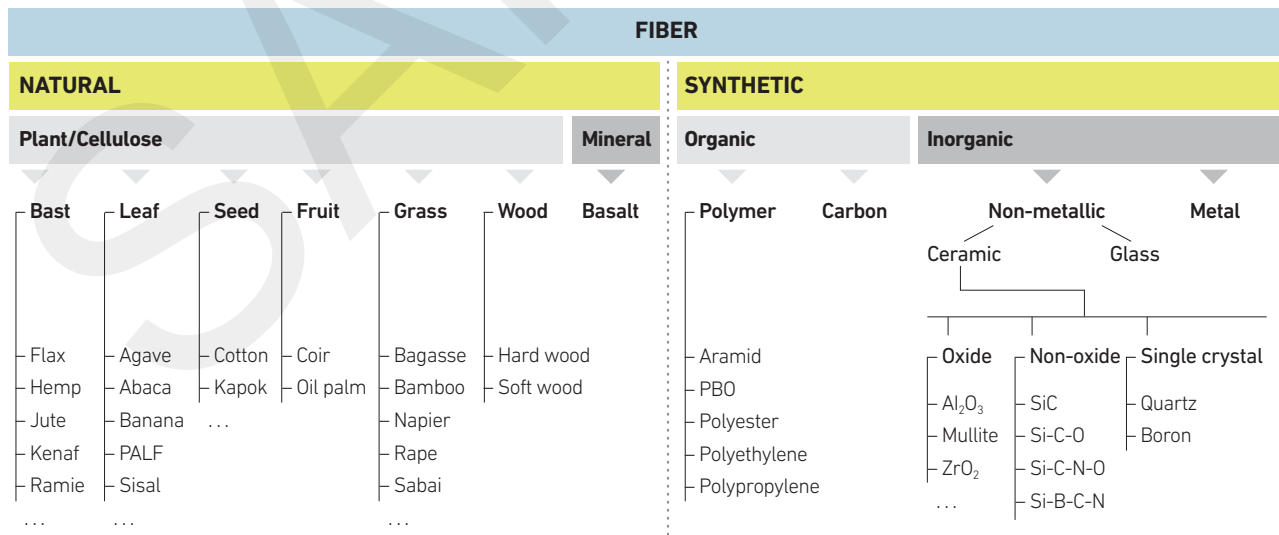


FIGURE 3-3. Types of fibers used in composites.

Note: Modified from (1) “Fibers for Ceramic Matrix Composites” Clauss, B., in *Ceramic Matrix Composites*, pp.1-22, Walter Krenkel, Ed., © 2008 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim; and (2) “Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review” Jawaid, M.; HPS Abdul Khalil, in *Carbohydrate. Polymers* 2011 (Vol. 86, pp. 1 – 18).

Manufacture

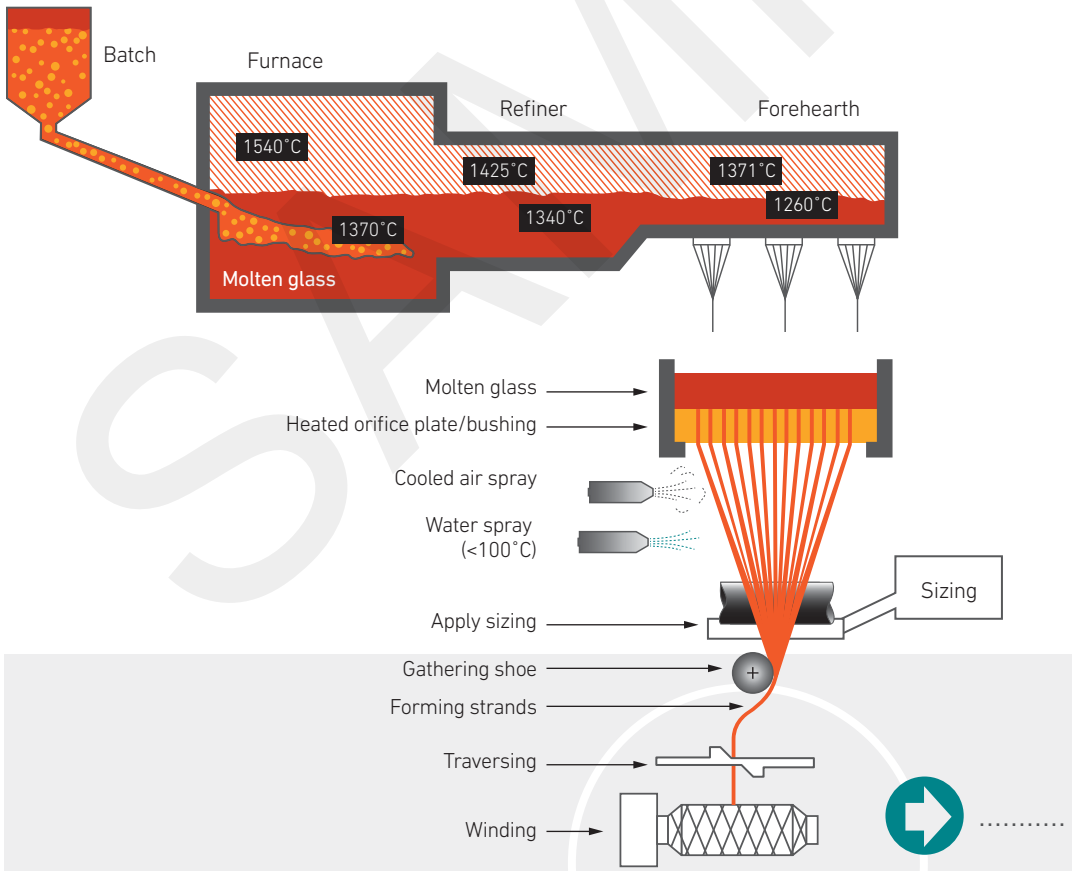
Textile-grade glass fibers are made from silica (SiO₂) sand which melts at 1,720°C/3,128°F. Though made from the same basic element as quartz, glass is amorphous (random atomic structure) and contains 80% or less SiO₂, while quartz is crystalline (rigid, highly-ordered atomic structure) and is 99% or more SiO₂. Molten at roughly 1,700°C/3,092°F, SiO₂ 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 SiO₂, Al₂O₃ (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.



(continued)

FIGURE 3-4. Glass fiber manufacturing process.



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