

3 Properties of Fibers

GLASS FIBERS

Glass fibers, also known commercially as 'fiberglass', are most extensively used as reinforcements for polymer matrix composites due to their combination of low cost, high strength and relatively low density. Unlike carbon or Kevlar fibers glass fibers are isotropic thus avoiding loss of properties when loaded in the transverse direction. Fiberglass is produced by pulling molten glass through orifices at a temperature where the glass has just the right amount of viscosity. A schematic of one of two common glass manufacturing processes is shown in Fig. 3-1. This process starts with solid glass beads

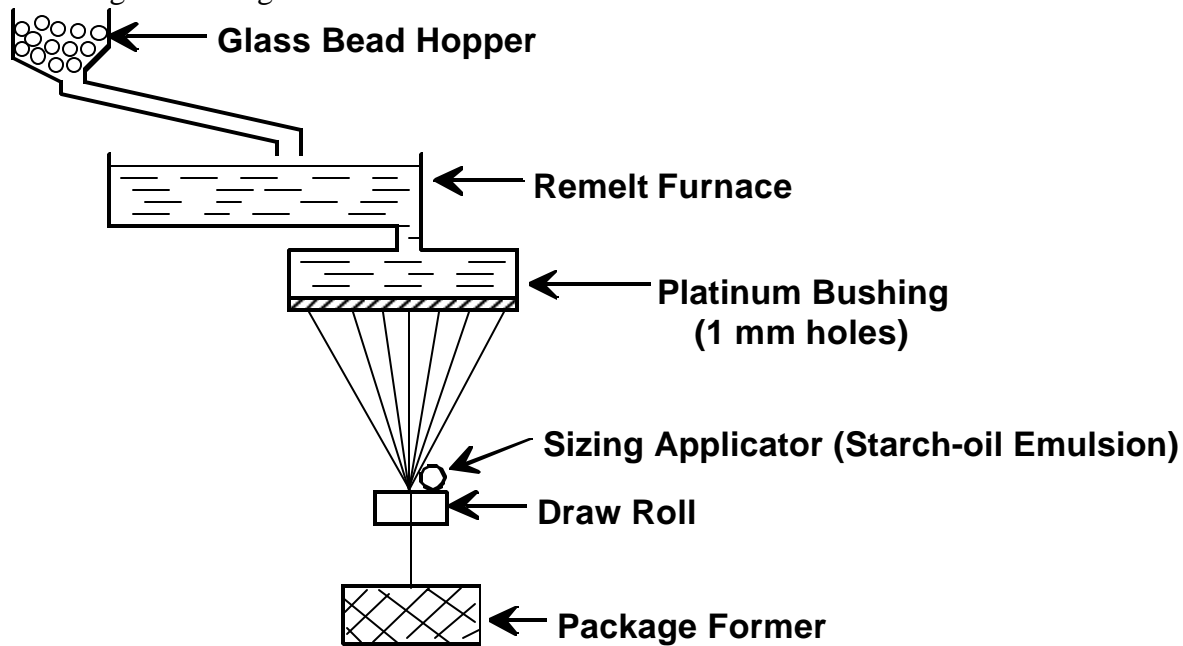


Figure 3-1. Schematic diagram of the remelt method of producing fiberglass.

(marbles) that are remelted and metered into a drawing box, the bottom of which contains holes lined with platinum bushings. From three hundred to three thousand such bushings, which act to meter out the right amount of glass, may be used. The fibers are formed into a continuous filaments by high-speed precision winders (Draw Rolls). Various size fibers, from 10 μm to 40 μm , can be formed from the same bushing diameter by changing the speed of the drawing roll. A chemical treatment, usually referred to as "sizing" or "binder," is applied to the filaments during the winding process to coat the filaments and reduce filament breakage during subsequent processing steps. These basic fiber glass strands (each strand is composed of filaments) are then twisted to achieve a product which meets the requirements for further processing. Single yarns can then be converted to plied yarns by twisting two or more singles together in a second twisting operation.

In addition to various diameters, glass fibers can have different compositions (these are listed in Table 3-1. Interestingly, the glass composition most commonly used in fibers for composites was developed to maximize its electrical resistivity rather than strength. The so-called E-glass is relatively inexpensive but possess sufficient strength to make it an ideal reinforcement for many organic matrix composites. The composition specifically developed for composite reinforcement is designated S-glass. This compositions is used for critical structural applications such as found

in the aerospace industry. S-glass is much more expensive than E-glass, not so much as due to the composition difference as due to the rigorous inspection and qualification procedure required for the aerospace industry. The cost of the S-glass composition can be significantly reduced if the stringent material specification (ASTM D578-90) is not required. This fiber is referred to as S-2 grade. The other common grade have been formulated for thermal insulation (A-Glass) and for chemical resistance (C-Glass).

Table 3-1. Composition of various glass fiber grades

Designation	Use	Composition
E	Electrical Insulation	55%SiO ₂ , 11%Al ₂ O ₃ , 6%B ₂ O ₃ , 18%CaO, 5%MgO, 5%Other
S	High Strength Composites	65%SiO ₂ , 25%Al ₂ O ₃ , 10%MgO (Strength Expensive)
S-2	High Strength Composites	Same as above but less stringent QC
A	Thermal Insulation	72%SiO ₂ , 1%Al ₂ O ₃ , 10%CaO, 3%MgO, 14%K ₂ O
C	Chemical Applications	65%SiO ₂ , 4%Al ₂ O ₃ , 6%B ₂ O ₃ , 14%CaO, 3%MgO, 9%K ₂ O

Mechanical strength

Strength comes from

The glass fibers produced in this manner can approach the theoretical strength of glass. This is because the fibers are nearly flaw free when they solidify. The high cooling rate in the draw zone prevents macro-defects from forming. However even the modest handling required to wrap the fibers onto the forming package and introduces sufficient flaws to significantly lower the tensile strength. Fibers that are immediately form and prior to any other handling treatment are referred to as virgin fibers. Table 3-2 shows the strengths of various types of glass fiber in the virgin state and after they have been wrapped onto a forming package. S-glass loses ~25% of its strength due to that handling. However, even after this loss the strength of S-glass is astoundingly high. E-glass, which has stiffness and densities similar to aluminum has strengths eight times greater than aircraft quality heat treated aluminum alloys such as AA6061-T6.

Environmental and corrosion resistance

Glass fibers are resistant to oxidation and moisture. Because glass fibers do not absorb water they do not swell, stretch or disintegrate. Glass fibers do not rot nor do they lose strength in humid environment. They can be considered mostly inert and resistant to many organic and inorganic reactants including many acids with the exception of H₃PO₄ and HF. Glass fibers are also resistant to solvent, oil and fuel.

Table 3-2 Strength of various glass fibers at different stages of processing

Fiber	Virgin		Forming Package	
	GPa	ksi	GPa	ksi
S-glass	7.00	1000	5.00	725
E-glass	3.70	537	2.80	406
Pyrex	2.00	295	1.60	230

Heat and fire resistance

Glass fibers are mixture of oxides and therefore do not burn in air or oxygen, however they can soften, melt and fuse at high temperatures (850 to 900 °C).

Thermal conductivity

The thermal conductivity of glass fiber is low compared to most structural materials but high compared to organic matrix materials. Table 3-3 lists the room temperature thermal conductivities of E-glass and other materials.

Table 3-3 Coefficients of thermal conductivity of various materials compared to E-glass

Material	Thermal conductivity, $\text{Wm}^{-1}\text{K}^{-1}$
E-glass	10.4
Aluminum (pure)	188
Copper (pure)	398
Steel	17
Carbon (graphite) parallel to basal planes	121
DGEBA (epoxy)	0.24

It is particularly relevant to compare the thermal conductivity of E-glass with Carbon (graphite) and DGEBA (epoxy). Carbon (graphite) is also used extensively as a reinforcement in advanced composites and has over ten times the thermal conductivity of E-glass. DGEBA is a commonly used epoxy for both E-glass and carbon (graphite) fibers. Since the thermal conductivity of DGEBA is so low the conductivity of the fiber has a very important influence on the thermal properties of the composites containing epoxy matrix.

Thermal expansion

The coefficient of thermal expansion of E-glass is very low. This characteristic of glass is often used to add thermal dimensional stability to composites. For example, E-glass milled to 6mm length are added to polyurethanes used in automotive facia to make a better match with the thermal expansion properties of steel. Table 3-4 lists the coefficient of thermal expansion for several materials.

Table 3-4 Coefficient of thermal expansion of E-glass and several other materials

Material	Thermal expansion, $10^{-6} / ^\circ\text{K}$
E-glass	5
Aluminum (pure)	25
Steel	13
Carbon (graphite) parallel to basal planes	2.25
DGEBA (epoxy)	66

Electric properties

Glass fibers are very good electrical insulators. The dielectric strengths of E-glass and various ceramics are shown in Table 3-5.

Table 3-5 Dielectric strengths of E-glass and various ceramics

Material	Dielectric Strength, V/mil
E-glass	498
Alumina	160
Porcelain	400
Fosterite	240
Titanium dioxide	210

Density

Glass fibers have low densities compared to other engineering materials. Table 3-6 compared the densities of various glass fibers with other fibers and structural alloys.

Table 3-6 Densities of various fibers and alloys

Material	Density, g/cc
E-glass	2.54
S-glass	2.48
Carbon fiber (graphitic)	1.95
Carbon fiber (carbonaceous)	1.63
Kevlar 49	1.44
Aluminum Alloy	2.70
Titanium Alloy	4.43
Steel	7.89
DGEBA (epoxy)	1.16

Compared to most engineering alloys glass fibers have considerably lower density, however, compared to other fiber reinforcement, such as carbon fibers and Kevlar they are significantly heavier.

Other characteristics

Glass fibers have stiffness modulus near aluminum alloys, which is only 1/3rd that of steels. Although the as-drawn strength of glass fibers is very high they are subject to self-abrasion that can significantly reduce its strength. Compared to other finer reinforced composites glass fiber reinforced material has low fatigue strength. Glass fibers do not absorb water into their bulk, but they can attach water molecules to their surface forming a very thin softened layer. This adsorbed layer can have an important effect on the strength of the fiber since water and other surface active substances leads to surface microcracks. This effect is exacerbated by the applied sizing which tends to hold moisture on the fiber surface. If the moisture layer is replaced by a non-polar hydrocarbon the fiber strength can be increased. If it is replaced by a more aggressive surface active substance the strength of the fiber can be reduced as seen in Fig.3-2.

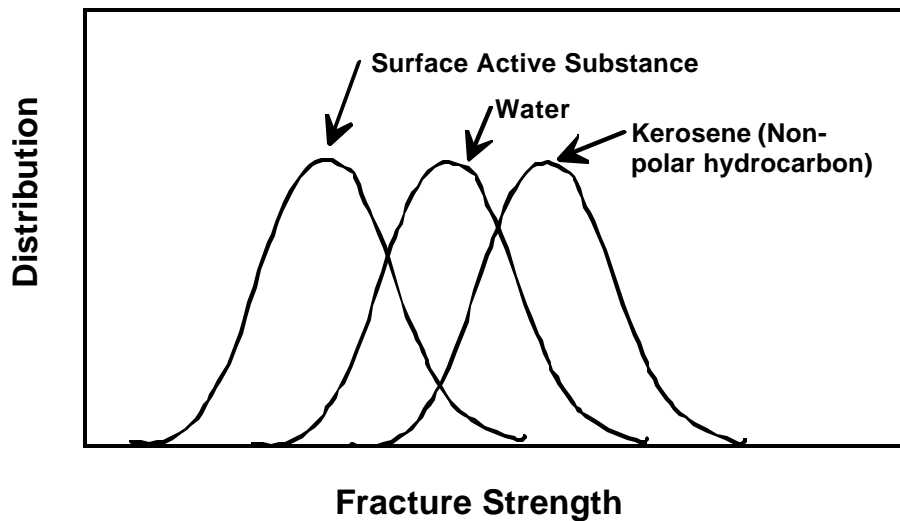


Figure 3-2. Effect of water and surface active agents on the strength of glass fibers

The surface effects are reversible. Removing the surfactant layer and replacing it with moisture or kerosene will increase the fiber strength.

CARBON FIBERS

Carbon fibers are used in advanced structural composites for aerospace and sporting goods industries. They are characterized by very high stiffness and low density. Some carbon fibers have a stiffness that are ten times and densities that are one half that of glass fibers. Although many carbon fibers have high strength, they are generally not as strong as glass fibers or aramid (Kevlar) fibers. The thermal properties of carbon fibers are outstanding. If they can be protected from oxidation above 1000°C they are stable to 2000°C. Above that temperature they will thermally decompose. Over a more modest temperature range, carbon fibers exhibits very low coefficients of thermal expansion; even negative thermal expansion in some cases. This characteristic allows the composite designer to achieve near zero expansion to temperatures as high as 300°C in critical structures such as spacecraft antennae. Carbon fibers are chemically inert and not susceptible to corrosion or oxidation at temperatures below 1000°C. Unlike glass fibers, carbon fibers have very high fatigue strength that is transmitted to their composites. Carbon fibers are electrically conducting, which is quite advantageous to the aircraft designer who must be concerned with the ability of an aircraft to tolerate lightning strikes. However, this characteristic poses a severe challenge to the carbon textile manufacturer because of the tendency of conducting weaving debris to interfere with electrical equipment.

There are a few other drawbacks to carbon fibers especially in comparison to glass fibers. The primary drawback is their cost. The lowest cost carbon fibers are twice as expensive as S-glass but some grades can be 100 times more expensive than E-glass. This high cost has excluded carbon fibers from many mass-market applications, such as the automotive market. They have found greatest use in areas where cost is not the primary consideration: military aircraft, spacecraft and sporting goods. Carbon fibers are quite anisotropic. Their strength and stiffness can be ten to 100 times greater in the fiber direction than in the transverse direction. Since

Structure and properties of the various grades of carbon fibers depend on method of manufacture. Historically there have been three types of carbon fibers depending on the starting or precursor material: reconstructed cellulose (Rayon), polyacrylonitrile (PAN) and mesophase pitch. Carbon fibers from cellulose (rayon) precursor are no longer produced because of the high cost of conversion to carbon or graphite.

Carbon fibers can contain varying amounts of graphite. It is the graphite structure that gives "carbon" fibers their desirable properties. Graphite has a layered structure, is anisotropic, and is an electrical conductor parallel to the basal planes. The structure is hexagonal (Fig 3-3) with ABABAB stacking in the basal (c) direction and layered planes normal to the basal direction. The bond strength is reflected in the crystal structure. Parallel to the basal planes the bond are very strong, however, normal to the basal planes the bonding is very weak.

There is another form of carbon with a cubic crystal structure called diamond. Bonding, bond length and structure are different between diamond and graphite. Large property differences between graphite and diamond exist due to these different bond forms. Table 3-7 shows a comparison of graphite and diamond properties.

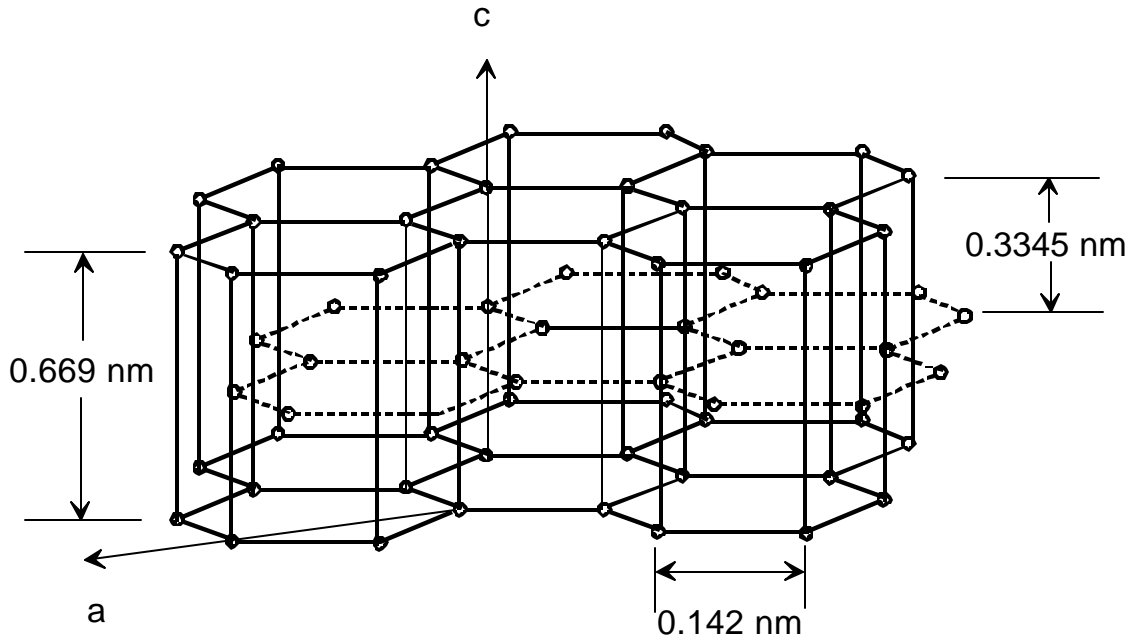


Figure 3-3. Crystal structure of graphite

Table 3-7 Physical properties of diamond and single crystal graphite

Property	Diamond (Cubic)	Graphite (Hexagonal)	
		a	c
Bond Length (nm)	0.154	0.142	0.334
Conductivity ($S^{-1}m^{-1}$)	$<10^{-15}$	250	0.05
Thermal Cond. ($Wm^{-1}C^{-1}$)	0.9×10^3	2×10^3	6
Thermal Exp. ($^{\circ}C^{-1}$)	0.8×10^{-6}	-1.5×10^{-6}	27×10^{-6}
Young's Modulus (GPa)	1200	1060	36.5
Hardness (Moh)	10	.5-1	
Density ($Kg m^{-3}$)	3300	2265	

"a" direction is parallel to the basal planes

"c" direction is perpendicular to the basal planes

The anisotropic properties of graphite are reflected in large difference in the extensional and shear stiffness in the graphite crystal when loaded in the various directions. Table 3-8 lists the compliance and stiffness coefficients for graphite. Notice that stiffness coefficient is almost 30 times greater in the direction parallel to the basal planes, C_{11} , than perpendicular, C_{33} , to them. The shear stiffness coefficient which acts to shear a basal plane, C_{12} , is 45 time greater than the shear coefficient which acts to slide the basal planes over one another, C_{44} . These effects are a direct consequence of the difference between covalent and Van der Waals bonding.

Table 3-8 Elastic constants of graphite

Compliance		Stiffness		Crystal Loading Direction
Coeff	10^{-4} GPa	Coeff	GPa	
S_{11}	9.8	C_{11}	1060	
S_{33}	275	C_{33}	36.5	
S_{44}	2500	C_{44}	4	
S_{12}	-1.6	C_{12}	180	
S_{13}	-3.3	C_{13}	15	

Young's modulus of a graphite crystal can be determined from the compliance coefficient according to

$$\frac{1}{E} = S_{11} \cos^4 \mathbf{f} + S_{33} \sin^4 \mathbf{f} + (S_{44} + 2S_{13}) \cos^2 \mathbf{f} \sin^2 \mathbf{f}$$

where \mathbf{f} is the angle between the loading direction and the basal planes.

Fig 3-4 shows the significant drop in Young's modulus as loading axis is rotated away from the basal planes.

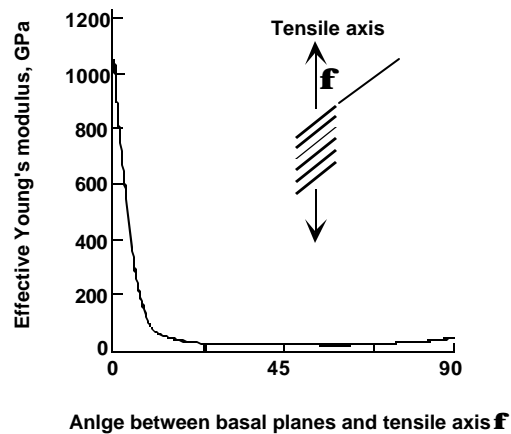


Figure 3-4. The effect of off-axis loading on the Young's modulus of graphite

Carbon fibers are actually composed of graphite and non-graphitic carbonaceous material. The graphitic phase present in the form of crystallites with discrete dimensions that can be oriented differently from each other. The very high stiffness carbon fibers contain a large portion of graphite aligned in the fiber direction as illustrated in Fig. 3-5.

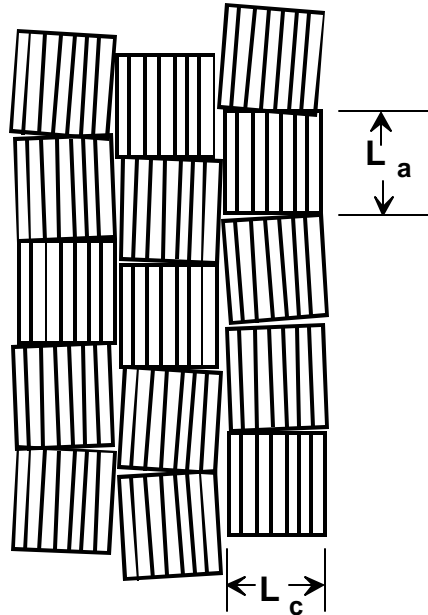


Figure 3-5. The representation of graphite crystallites in a carbon fiber.

Carbon fiber manufacture

The crystallite size, amount of graphite and orientation of the graphite in the fiber are controlled during their manufacture. Today there are two basic methods for manufacturing carbon fibers based on the starting material or precursor. The most extensively used method is the conversion of polyacrylonitrile (PAN) to carbon and then to graphite. PAN is formed by the polymerization of the acrylonitrile monomer, an olefin derived from the substitution of the nitrile group for a hydrogen as illustrated in Fig. 3-6.

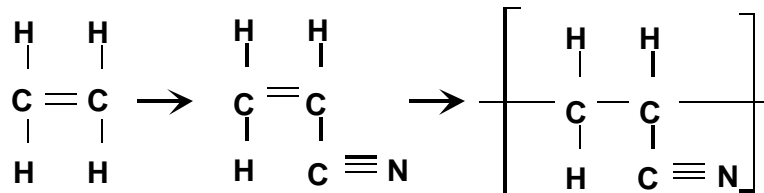


Figure 3-6. Ethylene acrylonitrile polyacrylonitrile sequence

The conversion of PAN to the various grades of carbon fibers is shown diagrammatically in Fig. 3-7. Carbon fibers are processed in a continuous line in which acrylic fibers are introduced as the

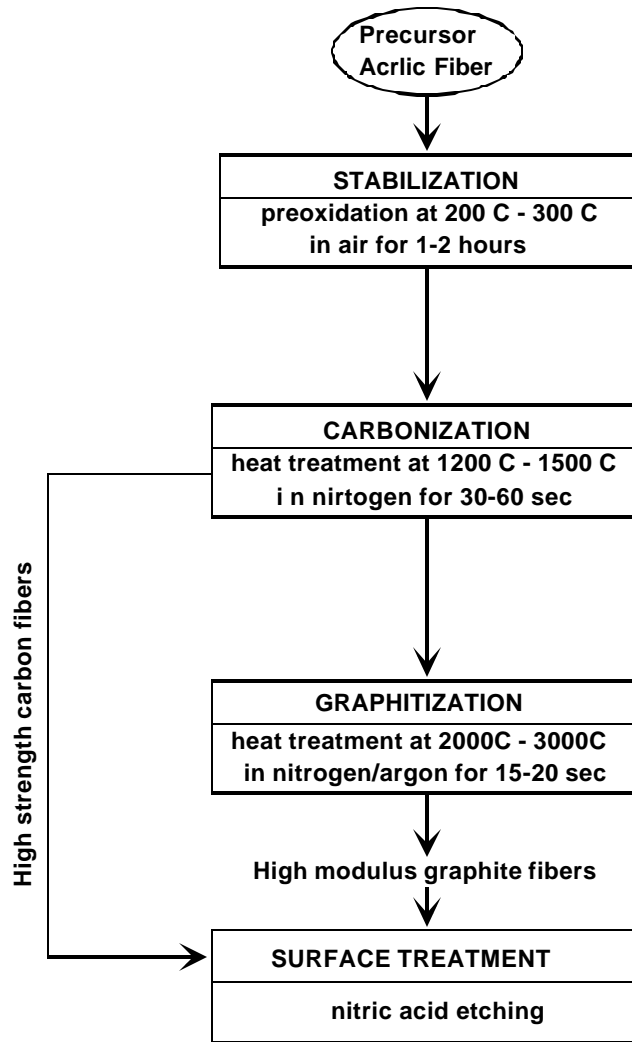


Figure 3-7. PAN precursor carbon fiber conversion process

starting material and emerge as carbon yarn. In the first step of this process the PAN fibers are heat to 200°C to 300°C in air for 1 to 2 hours while the fibers are in tension. Sufficient tension is used to unfold the tightly folded chain molecules. The oxidizing environment causes the unfolded chains to cross-link with oxygen molecules replacing a hydrogen molecules on adjacent chains. Excess oxygen carries the hydrogen away as water vapor. This intermediate product of cross-linked PAN is heat resistant and often used as a low cost fiber in heat resistant clothing under the trade name “CELIOX”. The fibers are then heated in nitrogen atmosphere at 1200°C-1500°C for 30 to 60 seconds. This heat treatment is referred to as the carbonization step and converts the cross-linked structure to the carbon ring structure. During this step excess water and hydrogen cyanide are evolved. The crystal structure is very small resulting in rather high strength. The fiber weighs on 50% of the original PAN fiber at this stage. This is the fiber form that is marketed as a low cost, moderate strength carbon fiber. The stiffness of this product is 200 GPa, which is a minimum for carbon fibers. In order to achieve higher strength and higher stiffness additional high temperature heat treatment is required.

This third stage of processing is called the graphitization treatment. The carbon fiber strands are heated in nitrogen/argon mixtures for 15 to 20 seconds at 2000°C to 3000°C. This treatment completes the conversion of remaining carbonaceous material to graphite. The graphite tends to align the basal planes in the direction of the fiber. During the process, however, the crystallite size can increase. The increase in graphite content results in increased stiffness while the increase crystallite size will lower the strength. This change in modulus and strength with graphitization temperature is shown in Fig.3-8.

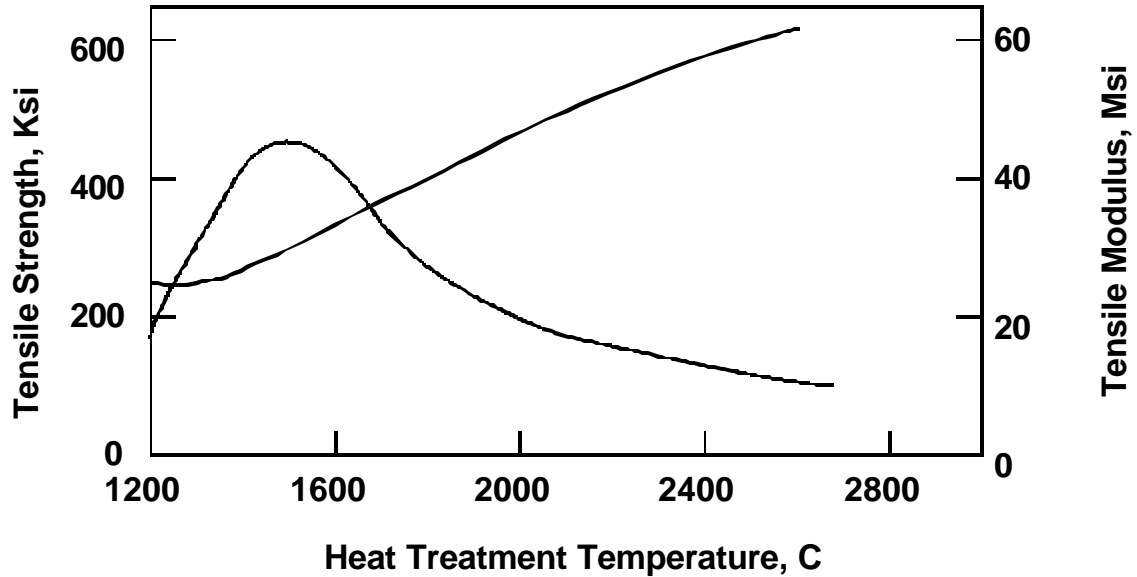


Figure 3-8. Effect of graphitization temperature on fiber properties

Increase in graphitization temperature results in initial increase in strength followed by a lowering above 1600°C. This effect has been attributed to the Hall-Petch effect which related fracture strength to grain size, d

$$s_f = s_0 + kd^{-1/2}$$

where s_0 is a characteristic strength and k a constant.

Fibers intended for use in epoxy matrix are oxidized in concentrated HNO₃ or oxygen to promote better adhesion.

Table 3-9 lists strength, stiffness and cost of various grades of PAN-based fibers. The fibers can be seen to fall into three groups depending on their stiffness, which in turn are determined by their degree of graphitization. The lowest stiffness PAN-based carbon fibers (Young's Modulus below 40 Msi) are generally referred to as high strength, (HS) fibers. They are also designated PAN Type II fibers. Carbon fibers with stiffness values between 40 to 50 Msi and are referred to as intermediate modulus (IM) fibers. Fibers with stiffness values between 50 and 60 Msi are called high modulus

(HM) fibers. They are also referred to as PAN Type I fibers. The ultra-high modulus (UHM) fibers have stiffness above 60 Msi. Carbon fiber costs reflect the cost of heat treatment. The stiffer the fibers require higher heat-treating temperatures to produce the greater amounts of aligned graphite.

Table 3-9. Properties and cost of PAN-based carbon fibers

Manufacturer	Designation	Modulus (Msi)	Strength (Ksi)	Cost (\$/#)
Hercules	AS2	33	400	
	AS4	33	520	21
Amoco	T300	32	450	26
	T650-35	35	645	28
Celion	G30-500	34	550	24
	G30-600	34	630	34
Graphil	AP38-750	38	750	
	AP38-500	33	500	16
	AP38-600	33	600	24
Hercules	IM6	40	745	48
	IM7	42	785	53
	XIM8	45	750	
	XMS4	48	400	
Amoco	T650-42	42	720	53
	T40	40	820	55
	T1000	42	1002	326
Celion	G40-600	43	620	45
	G40-700	43	720	47
	42-7A	42	725	59
Graphil	AP43-600	43	650	
Hercules	HMU	52	400	
Celion	G50-300	52	360	58
Graphil	AP50-400	50	400	55
	AP53-650	53	650	100
	AP53-750	53	750	110
Hercules	UHMS	62	325	325
Celion	GY-70	75	270	750
	GY-80	83	270	850

Carbon fibers can also be produced directly from petroleum or coal tar pitch. This method bypasses the preliminary manufacture of a polymer based textile fiber. The starting pitch material is heated to 400°C to 500°C for up to 40 hours to produce the mesophase state. The mesophase is a viscous carbonaceous soup which can be spun

directly into a precursor fiber. These raw fibers are stabilized by an oxidation treatment which causes thermosetting to occur. These so-called 'green' fibers can then be heat treated at high temperature to produce graphitization.

ARAMID FIBERS

Aramid fibers such as DuPont Kevlar are very important reinforcement for advanced composites. These fibers are based on the amide linkage formed by the reaction between carboxylic acid and the amine group. Fig 3-9 shows this reaction. When this linkage occurs between straight-chained-saturated molecules the results are aliphatic amides known commercially as Nylon. One such example is shown in Fig 3-10. When this linkage occurs between unsaturated benzene rings the results are aromatic amides called aramids (Fig.3-11).

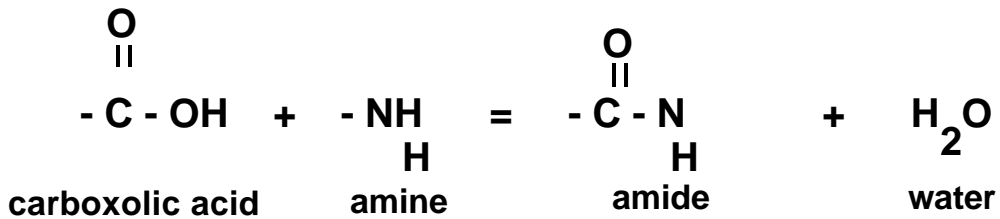


Figure. 3-9. The amide linkage

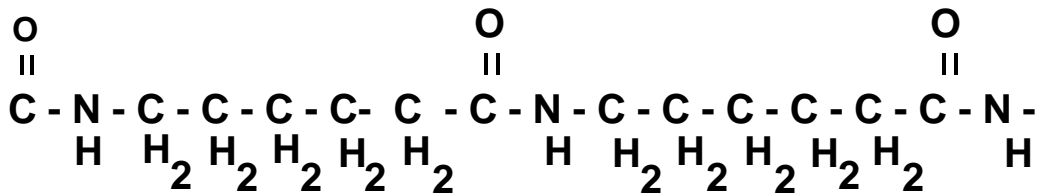


Figure 3-10. The structure of Nylon

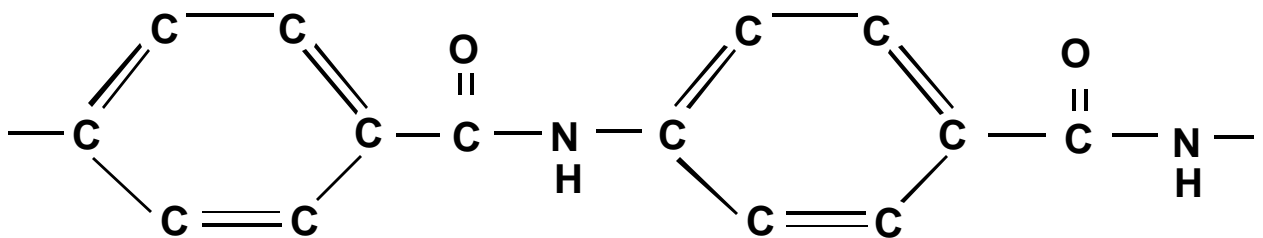


Figure 3-11. The structure of the aromatic amid, Kevlar.

The chain molecules of both types of amides are bonded by the 'hydrogen bonds' that are subject to disruption by ultra-violet light. The 'hydrogen-bond' is shown in Fig.3-12.

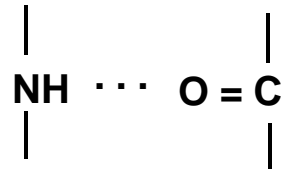


Figure 3-12. Diagram of the 'hydrogen-bond'

The aramid fibers are characterized by very high strength to density. Tensile strengths are typically 400 to 500 ksi. Kevlar 49 has a density of 1.44g/cc. The specific strength of Kevlar 49 fibers are 5 times that of steel. The elongation to failure is a little more than half of that for S-glass but still large compared to carbon fibers. Long term exposure to temperatures above 175°C will degrade the mechanical properties of aramid fibers. Like the highly graphitic carbon fibers, Kevlar 49 has a negative coefficient of thermal expansion. Aramid fibers are generally chemically stable but they are subject to attack by strong acids and bases.

One of the more serious limitations of aramid fibers is their degradation upon exposure to ultra-violet light. This degradation, however, only occurs in the presence of oxygen. These fibers also absorb water, coating are required to protect them from ultra-violet light, oxygen and moisture to assure reliable performance over long periods of time. Because the hydrogen bonds are much weaker than the molecular bond along the length of the fiber aramid fibers have poor transverse tensile strength, compressive strength and shear strength.

CERAMIC FIBERS

Ceramic fibers are used primarily in ceramic and metal matrix composites because of their high temperature strength and stability. They are, as a class, oxidation resistant and corrosion resistant, especially the oxide fibers. Mechanically they are characterized by high stiffness and low thermal expansion. Table 3-10 presents properties of some commercially available ceramic fibers that are used in composites. Unlike carbon and aramid fibers, ceramic fibers have high compressive strength. Ceramic fibers tend to have higher density than carbon fibers and some are even denser than glass fibers. Because ceramic fibers are strong and hard, composites containing them are very difficult to machine. Metal matrix composites with ceramic fibers generally are machined with diamond tools. Ceramic fibers are available in the form of textile fibers, whiskers and monofilaments. Each form represents a large difference in fiber diameter and is manufactured by unique methods for very specific applications. A visual representation of the fiber diameter difference for these three forms is shown in Fig. 3-13. Silicon carbide is an example of a ceramic fiber available in these three forms.

Silicon carbide textile fibers

Textile fibers of silicon carbide were first successfully developed Japan and are now marketed under the trade name 'Nicalon' by Nippon Carbon and Dow Corning. These fibers are based on the conversion of organosilicon polymers to an inorganic. The precursor organic material dimethyldichlorosilane is converted to polycarbosilane. This compound is heated at 280°C to adjust the molecular weight for spinability. The 'raw' spun fibers are cured by oxidation at 200°C to form the 'green' fibers. The curing process produces cross-linking with oxygen. The green fiber are then heat treated at 1500°C to release hydrogen, methane and carbon monoxide leaving mostly silicon carbide with some residual oxygen.

Table 3-10 Properties of commercially available ceramic fibers

Manufacturer	Designation	Composition	Tensile Strength, M Pa	Tensile Modulus, GPa	Density	Diameter μm
Nippon Carbon	Nicalon	50 Si, 31C, 10 O	2520-3290	182-210	2.55	10-20
Textron	SCS-6	SiC on carbon core	3900	406	3.0	143
3M	Nextel 312	62 Al ₂ O ₃ , 14 B ₂ O ₃ , 15 SiO ₂	1750	154	2.7	11
DuPont	FP	>99 % -Al ₂ O ₃	>1400	385	3.9	20
Sumitomo	(spinel)	85 Al ₂ O ₃ , 15 SiO ₂	1800-2600	210-250	3.2	9-17
Ube	Tyranno	Si, Ti, C, O	>2970	>200	2.4	8-10
Textron	polymer pre	Si, C	>2800	280-315		6-10
Dow Corning	MPDZ	47 Si, 30 C, 15 N, 8 O	1750-2450	175-210	2.3	10-15
Dow Corning	HPZ	59 Si, 10 C, 28 N, 3 O	2100-2450	140-175	2.35	10
Dow Corning	MPS	69 Si, 30 C, 1 O	1050-1400	175-210	2.65	10-15
3M	Nextel 440	70 Al ₂ O ₃ , 2 B ₂ O ₃ , 28 SiO ₂	2100	189	3.05	10-12
3M	Nextel 480	70 Al ₂ O ₃ , 2 B ₂ O ₃ , 28 SiO ₂	2275	224	3.05	10-12
DuPont	FP 166	Al ₂ O ₃ , 15-25 ZrO ₂	2100-2450	385	4.2	20

Silicon carbide whiskers

Silicon carbide whiskers are extensively used to reinforce ceramics for increased toughness. SiC whiskers are produced commercially by the pyrolysis of rice hulls. Typical properties of these whiskers are given in Table 3-11.

Silicon carbide monofilaments

Monofilaments are fibers with large diameters (100 to 200 μm). As a result, monofilaments have excellent compressive properties. The large diameter makes these fibers ideal for metal matrix composite processing since some degree of fiber reaction is permitted. The large fiber diameter has the disadvantage of limiting the amount of fiber bending before fracture. The larger the minimum permitted bend radius the greater is the brittleness of the fiber. The minimum permitted bend radius r_{\min} can be found by equating the bending moment at the fiber fracture strength, s_{fu} with the bending moment to achieve the critical curvature,

$$r_{\min} = \frac{ED}{2s_{fu}}$$

where E is Fiber Young's modulus and D is the fiber diameter.

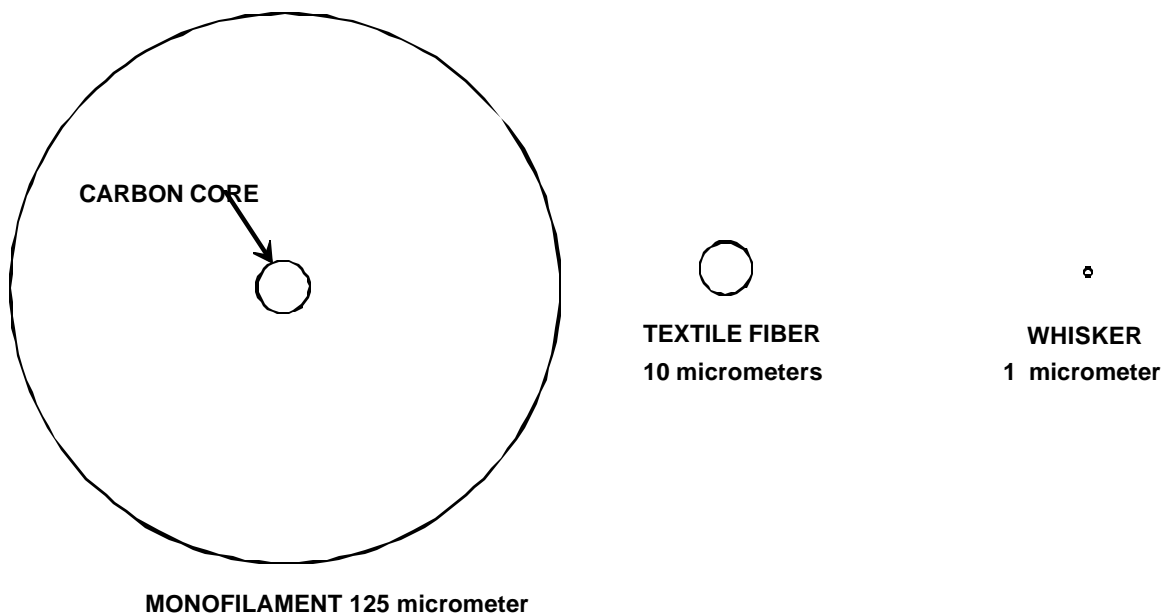


Figure 3-13 Comparison of the diameters of whiskers, textile fibers and monofilaments

Table 3-11. Typical properties of SiC whiskers.

Property	Value
Diameter (microns)	0.45 - 0.65
Length (microns)	10 - 80 (< 80%)
Surface area (M ² /G)	3.0
Density (G/cm ³)	3.2
Bulk density (G/cm ³)	0.2 (Approximate)
Tensile strength	
GPa	1.4 - 4.8
ksi	200 - 700
Elastic modulus	
GPa	420 - 690
Mpsi	60 - 100

The critical minimum bend radii of various fibers have been calculated by this method and are given in Table 3-12.

Table 3-12 Minimum bend radii of various fibers.

Fiber	F _f (GPa)	D (Microns)	E (GPa)	D _{min} (mm)
Carbon	2.1	11	520	1
Al ₂ O ₃ FP	1.4	25	345	3
SiC Filaments	3.5	9	300	0.5
B, Sic or Borsic	2.8	200	400	14
Tungsten	1.1	500	400	91
Tungsten (Fine Drawn)	4.1	75	400	4

Addendum to Chapter 3
Mechanical properties of various common fiber reinforcements

Fiber	Dia. μm	ρ g/cc	E GPa	E msi	σ_{TU} GPa	σ_{TU} ksi	ϵ_f %	α_l /°F	α_r /°F	ν
E-Glass	10	2.54	72	11	3.45	500	4.8	2.8	2.8	0.20
S-Glass	10	2.49	87	13	4.30	625	5.0	1.6	1.6	0.22
PAN C T-300	7	1.76	228	34	3.20	470	1.4	-0.1	7.0	0.20
PAN C AS	7	1.77	220	32	3.10	450	1.2	-0.5	7.0	0.20
PAN C T-40	6	1.81	276	40	5.65	820	2.0			0.20
PAN C HMS	7	1.85	345	50	2.34	340	0.6			0.20
PAN C GY-70	8.4	1.96	483	70	1.52	220	0.4			0.20
Pitch C P-55	10	2.00	380	55	1.90	275	0.5	-0.5		0.20
Pich C P-100	10	2.15	690	100	2.20	325	0.3	-0.9		0.20
Kevlar 49	11.9	1.45	131	19	3.62	525	2.8	-1.1	33	0.36
Boron	140	2.70	393	57	3.10	450	0.8	2.8	2.8	0.20
SiC	133	3.08	400	58	3.44	485	0.8	0.8	0.8	0.20
Al ₂ O ₃ FP fiber	20	3.95	379	55	1.90	285	0.4	4.6	4.6	0.20