Composites:
Lighter, Stronger, Better

An Explanation of What Composites Are, How They Work, and Why They Are Important

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February 2023

Printed in the United States of America

Dedication

To the sponsors of this book who have students in their corporate hearts and the future of the composites industry in their minds. With much thanks.

Project carried out with the support of the following:

Boston Materials

Airtech Advanced Materials Group

Ernest Solvay Fund managed
by the King Baudouin Foundation

KraussMaffei

Los Angeles Chapter of SAMPE

William Dahlgren Family

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Preface

I can still remember exactly where I was sitting in my high school chemistry class when Mister Grandy explained the periodic table and I had a flash of clarity. At that moment I realized that each element could be obtained from the previous one by simply adding a proton, an electron, and some neutrons for stability. I understood how the elements of the earth were likely made. It left me intrigued with a desire to learn more.

Figure 1 Discovery in a STEM classroom

A few years later, while studying chemistry in college, I could envision the movements of the atoms and molecules and I understood how their physical shape determined their mechanical properties. It seemed that the atoms and molecules were like friends and I could see how they could be arranged to create useful products for the world. I was especially impressed with the value of plastics. After a bit of research into the marketplace, I decided that my dream job would be working for the DuPont Company in the Plastics Division. After college I had that “perfect” job.

My first assignment at DuPont was to make roof tiles from a mixture of plastic resin, fiberglass, and a special powdered rock. We believed our tiles would be lighter, longer lasting, and easier to install than traditional roofing materials. My job was to determine the correct mixture proportions and molding conditions to make the DuPont roof tiles meet strength, flame retardance, and durability standards at a cost that was low enough to get into the market. I became amazed at how I could change the physical and flame-retardant properties of the mixture by varying the amounts of each component. I was also fascinated at how changing the length of the fiber and the molding conditions made so much difference in my ability to mold good roof tiles. I did some research and discovered that mixtures like mine were called composites and that composites had special physical characteristics that led to improvements in many products, including the Corvette. (I loved the Corvette.) I thought that composites would be a great field to focus on as a major part of my career. However, for the moment, DuPont had some other projects that they wanted me to learn about. Over the next few years, I worked in the laboratory, production plant, and directly with consumers on several new products. I was transferred to California and then, after two years on that product, DuPont asked me to return to Delaware for a new assignment. But, by that time my family wanted to stay in California.

I left DuPont to accept a job in San Diego with a company making plastic drip irrigation products and soon became the president of that company with sales around the world. I was delighted that our products allowed farmers to grow crops with higher yield and less water. We were helping to feed more people and saving water at the same time.

I loved the job but after a merger with another company, there were two presidents and I felt it was time to return to my home city and care for my parents. I accepted a position at Brigham Young University (BYU) where I taught plastics, composites, general materials, entrepreneurship, and a class on creativity. My research was mostly in the field of composites and plastics. I helped companies develop new airplanes, improve products for national defense, and create medical devices that saved lives. It was fulfilling.

Since retiring from BYU, I have worked for a non-profit company in Utah that brings together industry, universities, government, and national professional societies to assist the composites industry in Utah. This company is called the Utah Advanced Materials and Manufacturing Initiative (UAMMI). I call on companies to help them solve problems, hold seminars so that all of the participants can talk together easily and find out about the latest developments in the field of advanced materials, and help companies get grant money for research projects. I go to national conferences to keep current in the field and learn about new materials. I have found that such conferences, and membership in professional societies that sponsor the conferences, like SAMPE, has given my career a boost and has helped me stay informed with the latest.

Over the 27 years I was at BYU, I met with hundreds of students about their career goals. In most of those mentoring sessions, I asked the students “What do you envision yourself doing in 10 years?” After their response, I would then make some suggestions that I felt would help them get to that 10-year place. My recommendations often involved composites because I saw the growth potential of composites and the opportunities for contributing to the betterment of the world by using composite materials. However, I also recommended other careers when the student clearly wanted a different direction. In each case I have also recommended that the student pick some field that is both interesting and progressive where the student can become an expert. I have found it is always beneficial to study a subject in depth so that you can feel comfortable with working to advance the field and to study widely so that you can see outside your narrow field of expertise.

I am pleased to work with the SAMPE Foundation to create this book. Some great companies and other organizations, to whom I have dedicated the book, have contributed to the costs of producing the book. It is part of the STEM (science, technology, engineering, and math) program that has received a strong emphasis from the Federal and many state governments. STEM is helping create a stronger and more creative country.

The purpose of this book is to introduce students to composites and to explain how these special materials can help make the world better and create richer and fuller lives. Maybe you, too, will find your “perfect” job in composites where products are made stronger, lighter, and better.

Chapter 1 — National Priorities

The United States, like many other countries, has established a set of National Priorities. Some have been stated explicitly by the Federal Government and others are implicit but implied by the policies of the government. A list of these priorities is given in Table 1. Taken together, these priorities can be called Earth Stewardship and People Awareness.

Table 1 National Priorities

Improved energy management
Reduced pollution
Improved safety
Longer-lived products
Reduced corrosion
National defense
Technical superiority
Improved jobs

Composite materials make significant contributions to achieving these National Priorities. Each priority and the role of composites in achieving it are discussed in the sections that follow.

Improved Energy Management

At the most basic level, there are only a few usable sources of energy for our world. The most obvious and most important is the sun (solar heat and light). Others are geothermal (the energy present in the core of the earth that is manifested in volcanos and geysers), chemical (as in batteries), and atomic or nuclear. You might wonder about wind energy, the hydroelectric energy of stored water in dams, the energy in oil and coal, and the energy from natural gas. These energies (wind, hydro, oil, coal, natural gas) are derived from solar power. The heating of the earth and water causes winds, the water in dams comes from evaporated water that returns as precipitation. The energy in oil, coal, and natural gas comes from the conversion of sunlight in plants through photosynthesis and those plants give energy to animals, including humans. When the animals and plants are buried under pressure for long periods, they turn into coal, oil, and natural gas. Most of our electricity and power for our transportation systems are created from these sources. We spend millions of dollars every year searching for new sources of energy because it is so important to our world societies.

An interesting correlation is seen between standard of living (as measured by national Gross Domestic Product — GDP) and energy use. (See Figure 2.) As shown in the figure, as energy becomes more available and is used, the standard of living increases. When people have more power, they can employ machines to help them be more efficient and, consequently, accomplish more and have more income. Longevity of life also rises with access to energy.

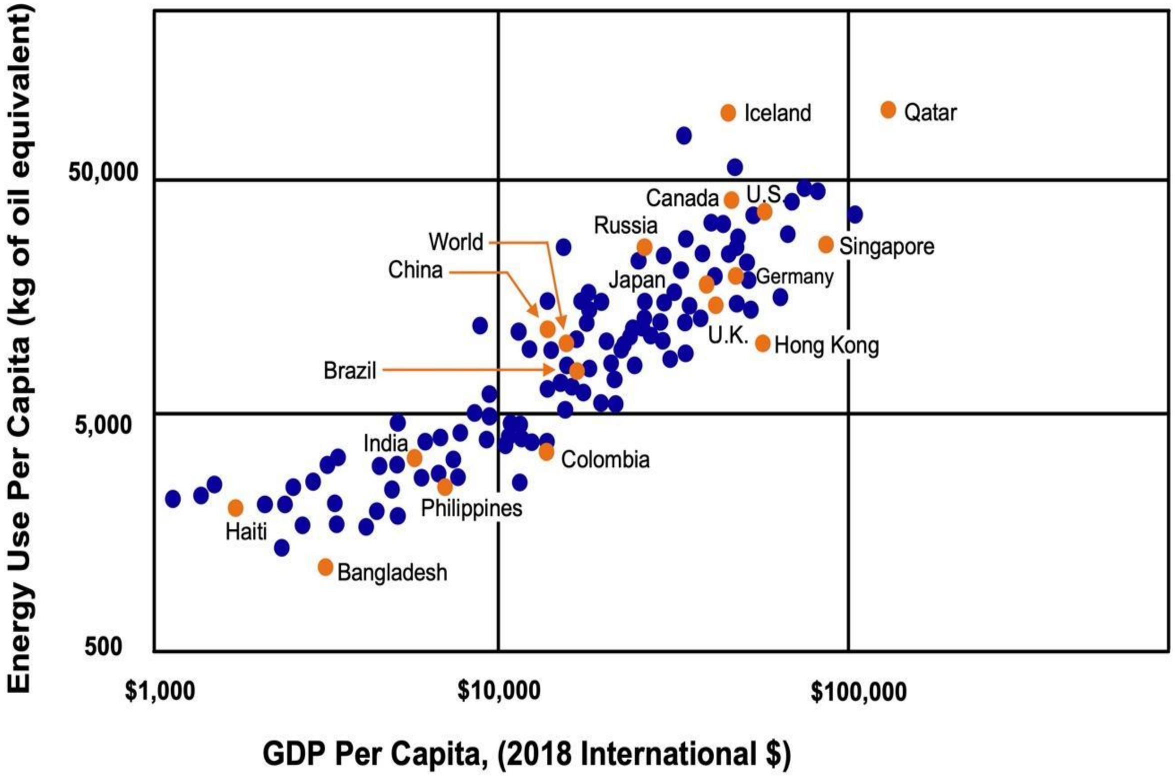


Figure 2 GDP versus Energy Use (Sources: International Energy Agency and World Bank)

Therefore, countries all over the world are demanding more access to energy. Since energy is limited both by ultimate availability and by ability to deliver it, we all should strive to conserve energy and to use the sources that are most renewable. This energy conservation helps our own country and, ultimately, every other country on earth.

One example of the use of composites to use energy more efficiently is wind turbines. The blades are made of fiberglass composites with carbon fiber composites as a stiffener. The production of wind turbine blades has become one of the largest uses of composites and is likely to grow as wind energy production continues to be more popular. Moreover, the efficiency of the turbines increases as the blades get longer, thus suggesting that the amount used, especially carbon-based, will become greater.

Figure 3. Composite wind turbine blades

Another application where composites are saving energy is in automobiles. Beginning in 1953, fiberglass composites were used to make Corvette hoods and other body panels. Since then, nearly every automobile model has used composites. Today, with requirements for greater fuel efficiency, carbon fiber composites are beginning to be used in many parts previously made of steel because the composites allow automakers to lighten their cars even more. One example is from BMW where an entire car body, including the frame, was made using carbon fiber composites and the reduction in weight was dramatic as shown in Figure 4.

Figure 4 Carbon fiber composite car body

Another way in which composites are helping us to use energy more efficiently is with pressure tanks that can be filled with hydrogen gas and used as fuel. Hydrogen is an excellent fuel because the only byproducts of its combustion are energy and water. Moreover, because hydrogen has not previously used widely, so its use will increase the total amount of energy available. A typical hydrogen tank is made from carbon fiber composites and is fitted into the trunk of a car as shown in Figure 5.

Figure 5 Hydrogen fuel tank made from composites

Reduced Pollution

Most people realize that automobiles are a major source of pollution for the world. Auto companies have done much to improve fuel efficiency and reduce pollution by changing the shape of cars to have less wind resistance, reducing the thickness of metal used, improving the operation of the engine, adding catalytic converters, and numerous small changes. But the major car companies now say that to meet the pollution standards that have been mandated, a major reduction in weight is needed. As already discussed above, the use of carbon fiber composites is the enabling technology for this weight reduction. But how much of a difference will it make to air pollution? As shown in Figure 6, reducing vehicle weight by 50 to 70% will reduce emissions by 40%. With this reduction it will create a pathway to meet emission standards.

Figure 6 Emission reduction from mass (weight) reduction

Boeing and Airbus make airplanes that are sold to the airlines around the world. Over the last 40 years they have gradually included composites in their airplanes. The latest models of airplanes, the Boeing 787 and the Airbus A350, both have their entire frame and body of carbon fiber composites. Both companies have seen major improvements in fuel efficiencies and reductions in emissions with these planes. The composite bodies also allow greater passenger comfort with more natural air pressures and increased cabin height and window size.

Improved Safety

When automobile manufacturers began considering the use of composites in the frame and other structural components of their cars, the question arose about the safety of composites in absorbing the energy of a collision. Testing was done at independent universities and it was discovered that composites absorbed more energy than either steel or aluminum. This higher energy absorption in the frame means that less energy is transferred into the passenger area and possibly injuring the passengers. As a result, cars with composite components are significantly safer than either of the major metals used in autos. This comparison is shown in Table 2 where the highest number is best.

Table 2 Energy absorption in automobile crashes for various materials

Composites	100 J/g ← Best
Steel	20-25 J/g
Aluminum	35 J/g

Longer-lived Products

We appreciate and tend to purchase products that last longer, all other factors being equal. In autos, the longer lasting car often has a longer warranty and so the overall cost of purchase and repair is often lower because of that durability. We realize that when materials are flexed up and down or back and forth, perhaps during normal use, the longevity of the product is reduced because cracking and other failures are initiated and amplified. When the flexed part is a key component for performance, like an airplane wing, avoiding the formation of cracks and keeping the original strength is critical. This is called retention of properties.

As shown in Figure 7, graphite (carbon) composites have a better retention of properties than aluminum, steel, or fiberglass after 10^5 (100,000) cycles and that superior performance gets better as the number of cycles increases further. This better property retention has been a major advantage for the Boeing 787 and the Airbus A350 and is expected to be an advantage for sports and recreation products, cars, and many other products that experience flexing.

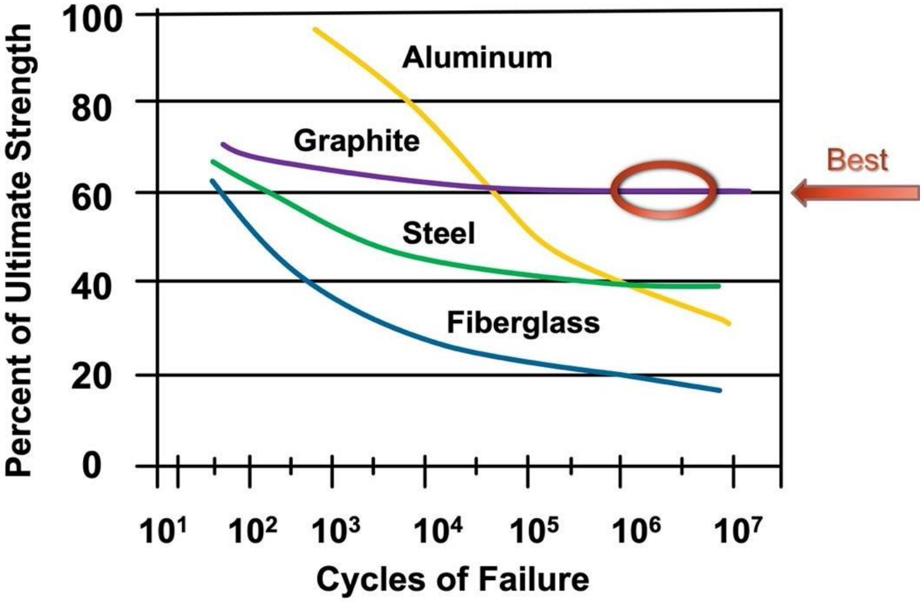


Figure 7 Comparison of Fatigue Strengths of Graphite, Steel, Fiberglass and aluminum. Note the greater strength of Graphite after 10,000,000 Cycles

Reduced Corrosion

Most structural metals like steel and aluminum are susceptible to corrosion. This is a process where the metal is chemically destroyed over time. The problem is especially troubling in pipes and ships as shown in Figures 8 and 9.

Figure 8 Pipe corrosion

Figure 9 Ship hull corrosion

Increasingly composites are being used for pipes and recreational boats, in part, because fiberglass composites don’t corrode. Large ships have been slower to adopt composites but some are now being used by the navy. Most pleasure crafts are made of fiberglass composites.

National Defense

Most people realize that the latest airplanes, rockets, missiles, and helicopters are made using carbon fiber composites. In all these cases composites reduce the weight, increase range, improve maneuverability, and allow greater speed. For rockets in the days when the U.S. was going to the moon, the use of composites for the rocket body dramatically increased the amount of weight (in fuel and people) that the rocket could carry and still gain orbit. Composites have allowed the latest airplanes to be stealthy, thus increasing their ability to engage enemy aircraft more effectively and to avoid detection when approaching a target.

The methods and materials used to achieve stealth are secret, but some details can be published. When the B-2 stealth bomber was being built, the emissions and reflections resulting from all the detection methods shown in Table 3 were minimized.

Table 3 Emissions and reflections considered for the B-2

Radar
Infra-red
Visual from ground
Visual from above
Visual from other aircraft
Sound
Con-trail (visual)
Radio transmissions
Ultraviolet
X-ray

Even though the B-2 is difficult to detect, it is not a small airplane. That is understood by comparing it to a B-52, the major bomber used in the Vietnam War. That comparison is given in Figure 10.

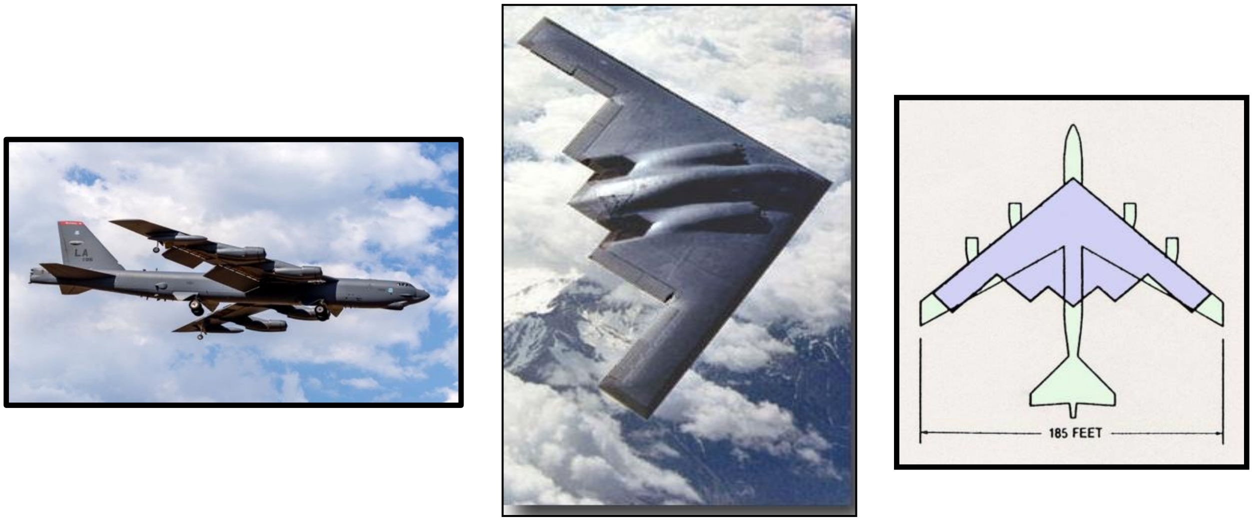


Figure 10 Size comparison of the B-2 and the B-52

The most convenient method of measuring stealth is to report the Radar Cross Section. That is, the size of the object as it would appear on radar. The normal units are square meters, and a person has a Radar Cross Section of about 1 square meter. Some typical airplanes and other objects are given in Table 4. As can be seen from the table, the B-2 has about the same radar cross section as a small bird. The latest jet fighter, the F-35, has an even smaller radar cross section.

Table 4 Radar Cross Section of Typical Airborne Objects

Object	Radar Cross Section (Square Meters)
Person	1
747 (Jumbo Jet)	100
B-17 (WWII)	80
B-47 (Korean War)	40
B-52 (Cold War)	10
B-1B (First Stealth)	1
Small Single Engine Airplane	1
Small bird	0.01
Insect	0.00001
F-117A (Stealth Fighter)	0.1
B-2 (Stealth Bomber)	0.01

The advantages of a small radar cross section are not only difficulty in being detected by enemy defense systems, but also superiority in plane-plane combat (dog fights) where the plane with the smallest radar cross section can see the opponent aircraft, shoot a missile, and then depart on a different trajectory before the opponent even detects the first plane’s presence.

Technical Superiority

For many years the United States has led the world in composite technology, much of it based on materials and manufacturing techniques developed in the aerospace industry and transferred to the private sector, especially to sports and recreation as well as medical. Figure 11 shows several products where this transfer of technology has resulted in superior products.

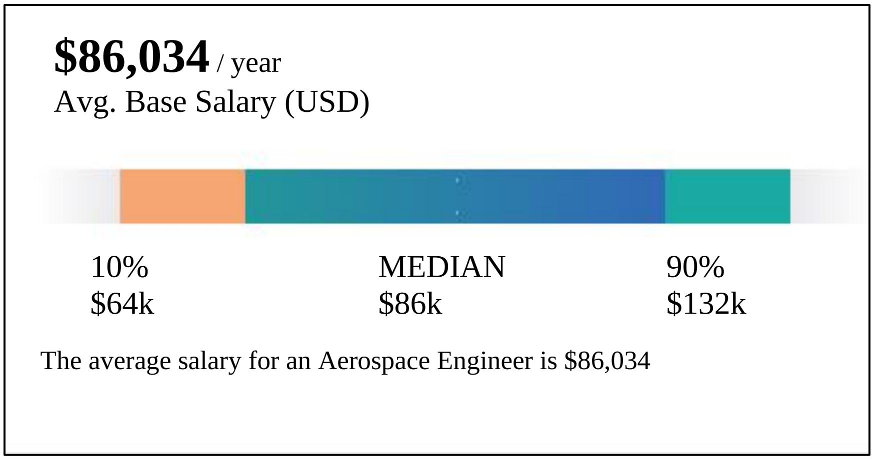
Figure 11 Composites in recreation and medical applications

However, many countries like China, Japan, India, and countries in Europe have seen the potential for growth and technological advantage of composites and have formed composites centers and have encouraged individual companies to be aggressive in their development of composites technology. The strong emphasis on solving environmental problems in Europe has been an especially strong area of progress for many of these companies.

All these countries need innovative people to enter the field of composites to continue the development of new products made of composites, including the transfer of concepts from aerospace and from other countries.

Improved Jobs

Composite jobs are in many different industries. However, the industry that employs many composite engineers is aerospace. Therefore, we can use that industry to get an idea of how much composite engineers and technicians make. The average salary for an aerospace engineer is $86, 034 (see figure below). By comparison, the average salary for all engineers is $72,000. Therefore, salaries for composite engineers are about 20% higher than the average of other engineers.



$86,034 / year

Avg. Base Salary (USD)

10%
$64k

MEDIAN
$86k

90%
$132k

The average salary for an Aerospace Engineer is $86,034

Figure 12 Average salary for aerospace engineer

Aerospace technicians (workers with no engineering college degree) also earn salaries higher than the average of other manufacturing technicians. In aerospace the average technician salary is $42,000 whereas the average for all manufacturing technicians is $33,700.

Composites Industry Growth

The potential for growth in the composites industry can be sensed by looking at the growth of the industry over the past few years and the predictions of experts for the next few years. That growth history and projection are shown in Figure 13.

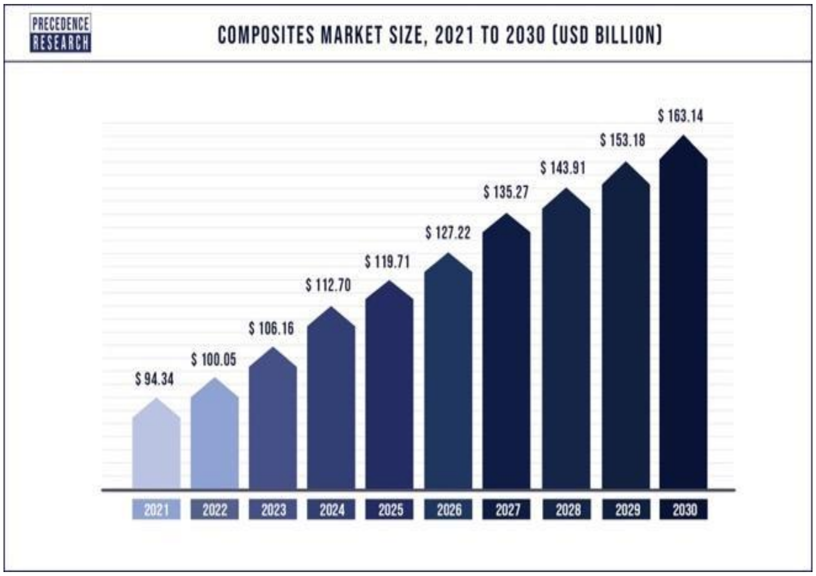


Figure 13 Growth history and projection for composites

While the projected growth shown is very satisfying, many experts see a much steeper growth rate in the future, especially as regulatory pressure is increased for improvements in auto emissions and the growth of electric vehicles, both of which are enabled by lighter weight cars and that means a higher use of composite materials.

The other market segments currently using composites are also growing rapidly. It is safe to assume that new markets for composites, not now readily apparent, will be found as engineers and product designers become ever more comfortable with these remarkable materials.

Some may worry that the use of composites compared to the use of other materials will be so high that there won't be room for composites in the overall use of materials. As shown in Figure 14, the current use of composites is only 1% of the total materials market.

This miniscule percentage for composites means that there is plenty of room for composites to grow. Composites is a field where the future is very positive.

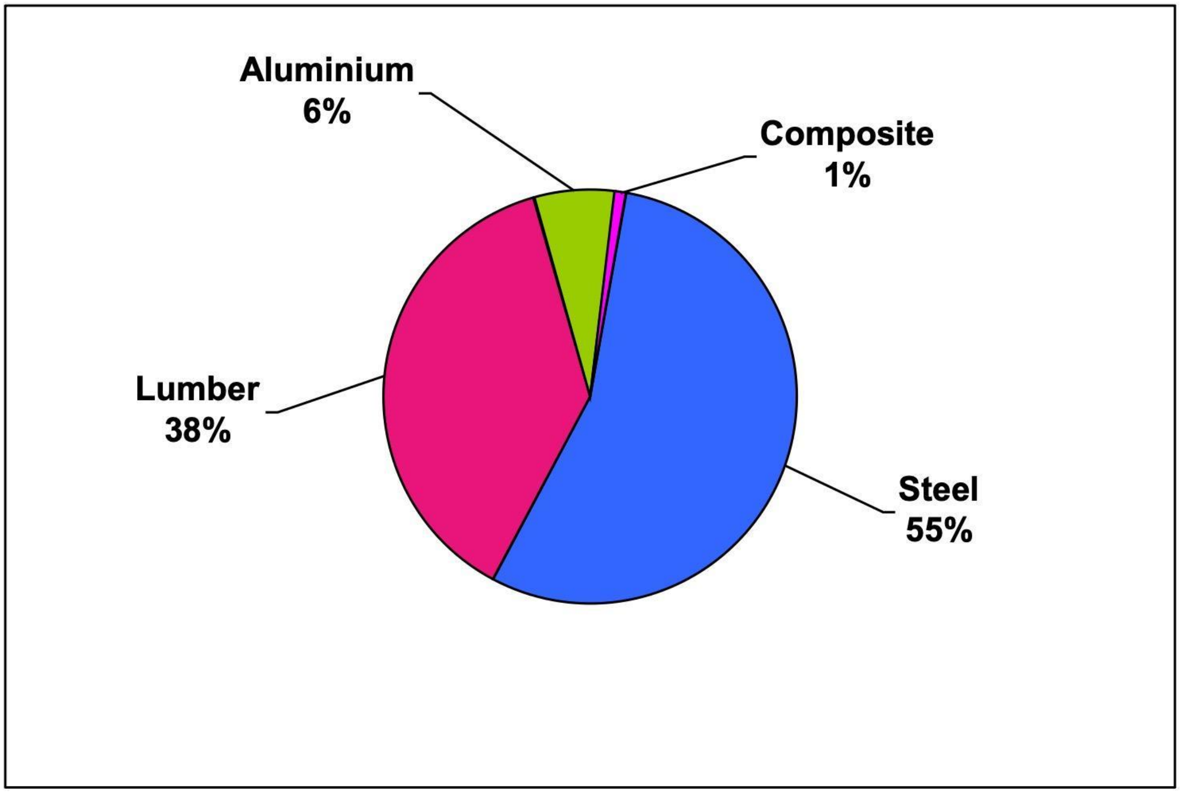


Figure 14 Composites share of materials markets

Chapter 2 — What Are Composites

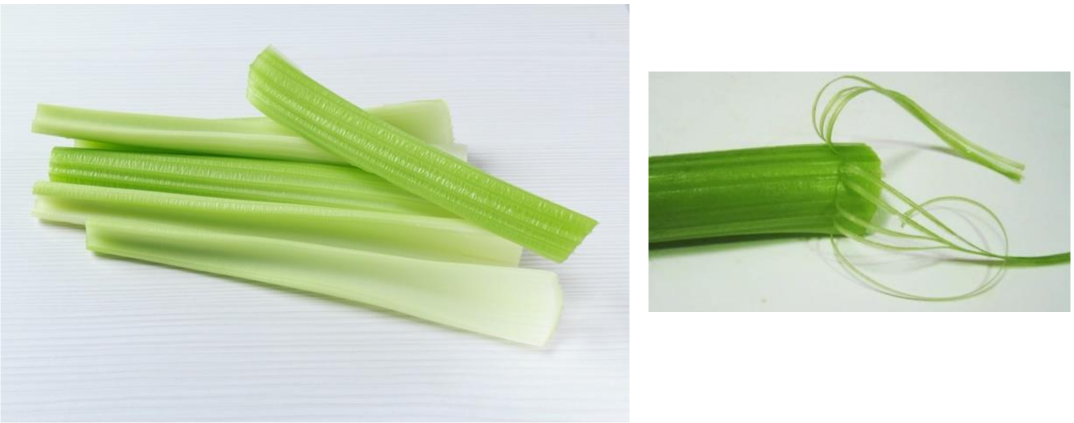
In the broad sense, the terms composites or composite materials refer to solid materials composed of more than one material where the materials are separate phases. In other words, the materials can, at least in theory, be seen separately and taken apart. Commercial examples are rebar in concrete or rocks in terrazzo flooring. Another example is fiberglass in plastic. These composites are shown in Figure 15. By this broad definition, there are so many types of components that an examination of them is impractical. Therefore, this book will focus on one major branch of composite materials—those that are fiber reinforced—a much narrower definition. A good working definition for the purposes of this book is: ***Composite materials are those solid materials composed of a binder or matrix that surrounds and holds in place fiber reinforcements.*** (Note: the terms binder and matrix are used interchangeably and both refer to the material around the fibers that holds them in place.) The reinforced fiberglass in plastic shown in Figure 15 fits this narrower definition.

Resins are very long molecules and are made up of many atomic units linked together in a chain-like formation. (Like people holding hands, one to another.) Each link in the chain is an atomic unit (a few atoms that form a group with particular properties) and is called a monomer (which means “one unit”). When put together in a chain, the entire chain is called a polymer (which means “many units”). Some polymer chains can have several thousand atomic units (links) while other polymers might have just a few.

In general, the term “resin” refers to polymers that are not yet in their final form and shape. After they have been molded or shaped, they are called plastics (from the Greek word for molded) although, in the case of composites, they are often called the matrix. Some composites, especially those with only a moderate amount of fiberglass reinforcement are called FRP (fiberglass reinforced plastics).

While many matrix/binders are possible, the binders of most importance are cured resins or plastics. When certain fibers are combined with certain binders, the resulting composites have special properties—they are synergistic. That is, the properties of the composite are greater than the properties of either of the materials (matrix or fibers) separately. It is almost like the fundamental arithmetic equation of 1 + 1 = 2 is changed to 1 + 1 = 3.

Nature has made many composites. One of the most familiar is celery and, as shown in Figure 16, the fiber reinforcements are clearly visible within the pithy matrix.



Other natural composites include bones within animal bodies, trees (especially trees where the fibers are obvious like bamboo), and many plants (especially those with high fiber content like jute, papyrus, flax, and hemp). Many of these plant fibers are extracted and used in modern composites.

The two components of composites—matrix/binder and reinforcement—are vastly different and have very different roles in the composite. The fiber reinforcements are strong and stiff but are susceptible to damage. The matrix resins are formable and protective, thus complementing the reinforcements.

It is important that the matrix completely surround and coat the surfaces of all the fibers. This means that the matrix is continuous, that is, fully connected with other parts of the matrix and with the reinforcements. The reinforcements are, therefore, the discontinuous phase. An analogy that is helpful in visualizing this is shown in Figure 17 where the ocean is like the matrix (continuous) and the islands are like the reinforcements (discontinuous). Note that the ocean completely surrounds and touches all the islands.

Figure 17 The ocean and islands are analogous to matrix and reinforcements

History of Composites

Early in history it was found that combinations of materials could produce properties superior to those of the separate components. For example, mud bricks reinforced with straw were better than bricks made only of mud. The reinforced bricked were used by ancient Egyptians and were described in hieroglyphic writings on the tomb of a nobleman in the Eighteenth Dynasty.

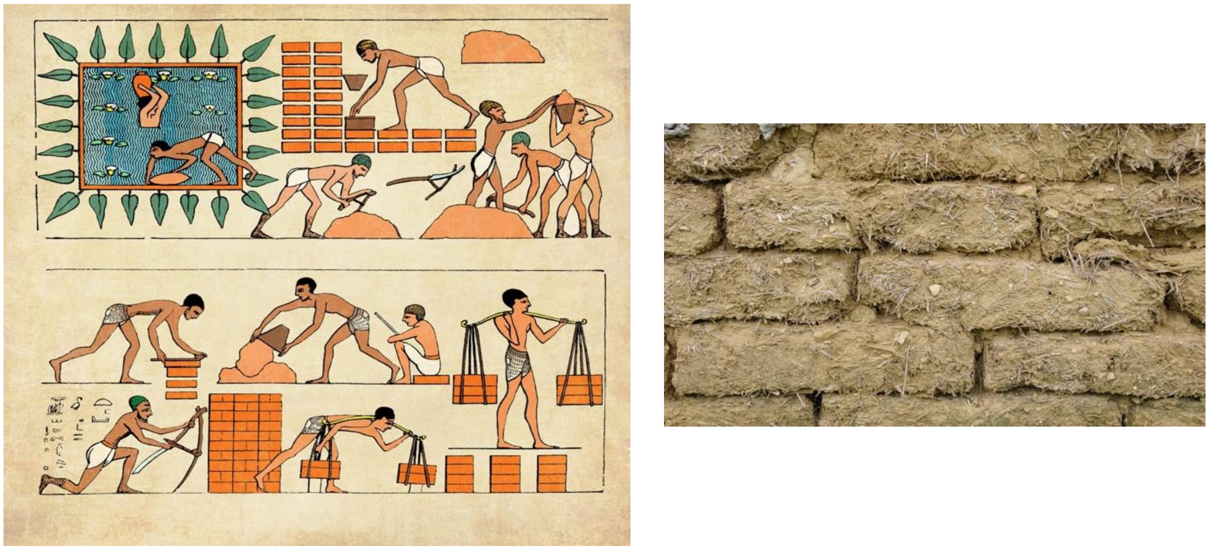


Figure 18 Egyptian hieroglyphs showing making of bricks and examples

Mongols made composite bows by bonding together (using glue made from animal hoofs and bones) five pieces of wood to form the core of a bow (center grip, two arms, two tips) to which cattle tendons were bonded on the tension side (away from the shooter) and cattle horns on the compression side (towards the shooter). This assembly was steamed and bent into the proper shape, wrapped with silk thread, and then cooled slowly (for up to a year) to create some of the most powerful bows ever made.

The history of modern composites (of the type discussed in this book) probably began in 1937 when salesmen from the Owens-Corning Fiberglas Company began to sell fiberglass to interested parties around the United States and those customers found that the fiberglass could serve as a reinforcement for plastic.

Fiberglass had been made, almost by accident in 1930, when an engineer became intrigued by a fiber that was formed during the process of applying lettering to a glass milk bottle. The initial product made of this finely drawn molten glass was insulation (glass wool), but structural products soon followed.

Figure 19 Glass milk bottle and fiberglass wool

The fiberglass salesmen soon realized that the aircraft industry was, in particular, a likely customer for this new type of material. Many of the small and vigorous aircraft companies seemed to be creating new aircraft designs and innovative concepts in manufacturing almost daily, and many of these new innovations required new materials.

One company, Douglas Aircraft, bought one of the first rolls of fiberglass because its engineers believed the material would help solve a production problem. They were trying to speed up the process of making molds for their sheet forming process. Each changed aircraft design needed new molds, and metal molds were expensive and had long times before the orders could be delivered. Douglas engineers tried using plastic molds, but those molds broke under the forces of the metal-forming process. The engineers reasoned that maybe if the plastic molds were reinforced with fiberglass, they would be strong enough to allow at least a few parts to be made. This would let the engineers test the new designs quickly. If the parts proved to be acceptable, then metal molds could be made for full production runs. Molds were made using the new fiberglass material and phenolic resin (the only resin available at the time). The test was a great success!

Other applications in tooling for aircraft soon followed. Many of the tools (molds, jigs, and fixtures) for forming and holding aircraft sections and assemblies needed to be strong, thin, and highly shaped, often with complex curves. Metals did not easily meet these criteria, so fiberglass reinforced phenolic production tooling became the preferred material for many of these aircraft manufacturing applications.

Not long afterward, unsaturated polyester resins (discussed in a later chapter) became available (patented in 1936) and they became the preferred resin to form the matrix. The unsaturated polyesters were preferred over the phenolics because of the ease of curing the polyesters. Higher performance resins also became available about this time with the invention of epoxies (1938), discussed in a later chapter. The materials and the applications seemed to be converging at the same time.

The fast pace of composites development accelerated even more during World War II. Not only were even more aircraft being developed and, therefore, composites more widely used in tooling, but the use of composites for structural and semi-structural parts of the airplanes themselves was being explored and adopted. For example, in the frantic days of the war, among the last parts on an aircraft to be installed were the ducts. Since all the other systems within the aircraft were already fixed, the ducts were required to go around the other parts. This often resulted in ducts that twisted and turned, often in the most difficult-to-access locations. Metal ducts just could not be easily made in those convoluted shapes. Composites seemed to be the answer. The composites were hand laid-up on plaster mandrels (internal molds), which were made in the required shape. Then, after the resin was applied to the fiberglass and cured, the plaster mandrels were broken out of the composite parts. Thousands of such ducts were made in numerous manufacturing plants clustered around the aircraft manufacturing/assembly facilities.

Other WWII applications included engine covers, radomes (domes to protect aircraft radar antennas), a structural wing box for the PT-19 airplane, and non-aircraft applications such as ship bearings, switch gears, brake linings, bayonet scabbards, and thousands of other applications.

About this time (1942), the United States government became concerned that the supplies of metals for aircraft might not be available. A major effort was initiated to develop the design rules and manufacturing methods for composites as possible replacements for aircraft metals. Several critical parts were made to prove out the design concepts and many creative manufacturing methods were developed.

During this critical period, many technical problems arose and the companies making composites decided to form a society that would coordinate meetings where the engineers in these companies could discuss the problems and mutually seek solutions. That society has continued to the present. It is called the Society for the Advancement of Materials and Process Engineering (SAMPE). SAMPE is now a worldwide organization with thousands of members in many local chapters and student chapters at many universities and technical colleges. SAMPE’s educational focus is very strong, including student contests, reduced membership rates, and other student-oriented programs. Most chapters have regular meetings and the national organizations hold major exhibitions and educational seminars each year.

When the war effort came to a halt, many companies that had been active in making war materials were faced with an acute problem. They needed to quickly identify new markets and new products that utilized the expertise they had developed. Some of this development work was supported by the materials suppliers. Some war-oriented applications were converted directly to commercial applications, such as fiberglass reinforced polyester boats.

Almost everyone agreed that the pent-up demand for automobiles was a logical application for composites. By 1947 a completely composite automobile body had been made and tested. This car was reasonably successful and led to the development of the Corvette in 1953, that was made using fiberglass and plastic. Some of the products made in the post-war era now represent major markets for composite materials. In addition to aircraft, these include boats, automobiles, tub and shower assemblies, non-corrosive pipes, appliance parts, storage containers, and furniture.

The push for aerospace dominance that began in the 1950s (during the Cold War) and picked up speed in the 1960s and 1970s gave a new impetus to further composite development. Hercules, Inc. was making rockets for the government using steel cases for the rocket motors and the engineers reasoned that using composites would lighten the rockets and increase the amount of fuel, cargo, and eventually people that could be carried. Hercules acquired a composite manufacturing technology called filament winding that allowed generally circular-shaped products to be made quickly and economically. Hercules began making small rocket motors using this equipment. In 1961 a patent was issued for producing the first carbon (graphite) fiber and Hercules acquired the rights to the patent and began making filament wound rocket motors with carbon fibers. The DuPont Company developed aramid (Kevlar) fibers about this time, thus broadening the selection of available composite fiber types. In 1978 the crowning jewel of this period was the development of the first fully filament wound aircraft fuselage, the Beech Starship.

Figure 20 Beech Starship

Recent material and process improvements and the development of higher performing fibers and resins have led to tremendous advances in aerospace, armor (structural and personal), sports equipment, medical devices, and many other high-performance applications. Composites have found their place in the world. Their use is increasing, especially in products where performance is critical. In 1989 the National Academy of Engineering issued its list of the top 10 engineering achievements of its lifetime (the 25 years prior to 1989). It ranked the development of advanced composites as number six on that list and cited especially advanced composite materials such as graphite-epoxy materials used to make lighter and stronger aircraft, bicycles, golf clubs, and other products. The academy said, "Composites add lightness and strength to a wide range of everyday objects."

Some composite product applications are very new, including stealth aircraft and space telescope structures, wholly composite bridges, and other construction edifices. As you can now see, from 1500 BC with the Egyptian bricks to now, composites have been a leading material helping to make some of the world's greatest achievements.

Several of the most common modern synergistic composites are:

- Fiberglass and unsaturated polyester,
- Fiberglass and nylon,
- Fiberglass and vinyl ester,
- Carbon fiber and epoxy,
- Carbon fiber and polyimide,
- Carbon fiber and phenolic, and
- Carbon fiber with carbon (char).

All of these common composites will be discussed in greater detail after the nature of fibers, the nature of matrices, and the design of composites have been discussed.

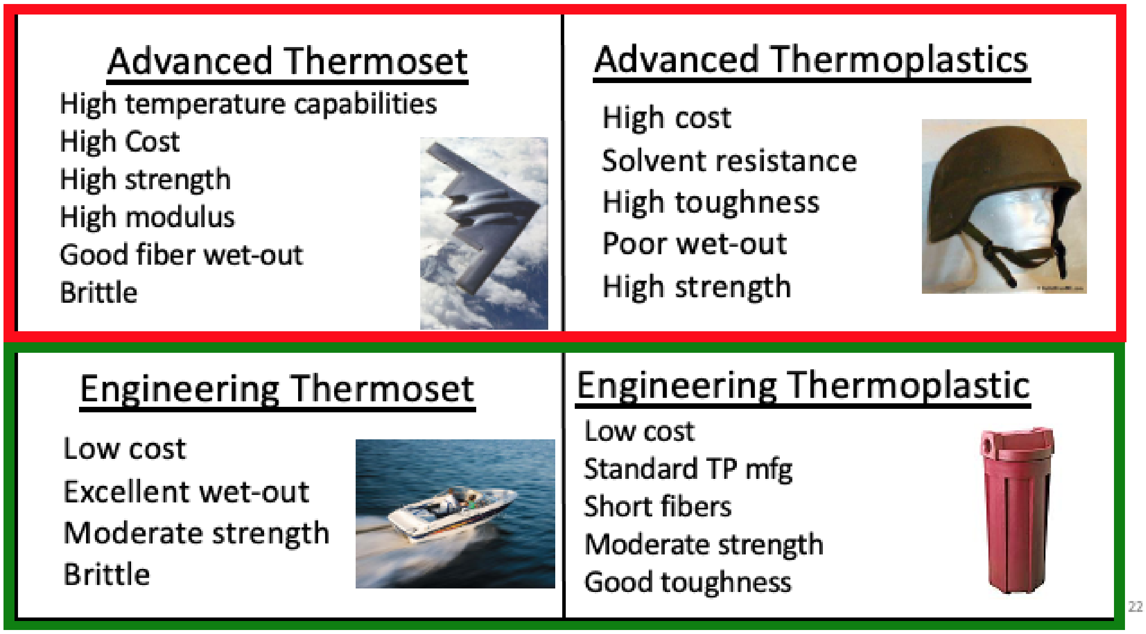
Advancements have been made in matrix materials just like advances in reinforcements. Several families of matrix materials have been developed for various applications. These families can be grouped as follow:

- polymer matrix composites (PMC)
- metal matrix composites (MMC)
- ceramic matrix composites (CMC)
- carbon-carbon (CC) composites

The most common of these matrix families is Organics (PMC)—Polymer Matrix Composites. This family will be the principal focus of this book.

Polymer Composite Types—Advanced and Engineering

Polymer matrix composites can be divided into four general subdivisions with two characterized by the types of matrices and two characterized by the types of reinforcements. Those divisions are shown in Figure 21



Advanced Thermoset High temperature capabilities High Cost High strength High modulus Good fiber wet-out Brittle	**Advanced Thermoplastics** High cost Solvent resistance High toughness Poor wet-out High strength
Engineering Thermoset Low cost Excellent wet-out Moderate strength Brittle	**Engineering Thermoplastic** Low cost Standard TP mfg Short fibers Moderate strength Good toughness

Figure 21 Polymer matrix composite types

The two matrix types—thermoset and thermoplastic—are shown on the right and left sides of the diagram. These two matrix types will be discussed in more detail in the chapter on matrices. The two reinforcement types are shown on the top and bottom and designated as Advanced (mostly carbon fiber composites) and Engineering (mostly fiberglass composites). Even though these four types have been distinguished in the marketplace and in this book, no sharp boundary exists and there are many products that crossover between the types. Still, the differences are valuable as a way to think about composites and to realize the major markets served by each of the types.

Advanced thermosets are the most common type for aerospace applications and high-performance sports equipment like golf club shafts, tennis racquets, and bows and arrows. Prosthetic feet and other artificial limbs are also in this category. In general, the reinforcement is carbon fiber and the binder/matrix is epoxy or, for special applications, polyimide.

Advanced thermoplastics are used in similar applications to advanced thermosets, but the thermoplastics do not have the same high temperature capability as thermosets. However, the thermoplastics are tougher, that is, they are less brittle and can take impacts better without cracking. Helmets are a good example. The thermoplastics also offer some processing advantages, especially in the speed with which the composite can be molded. In the 1990s the aerospace industry was moving toward greater use of advanced thermoplastics, but that movement died out because of problems encountered in process the high temperature thermoplastics. However, in the 2020s, the value of advanced thermoplastics and the solution of manufacturing problems previously encountered have led to a resurging of advanced thermoplastic applications.

Engineering thermosets are the most common composite type for large composite parts such as boats, large storage tanks, automobile body panels, and large pipelines. The reinforcements are usually fiberglass and the matrix materials are often unsaturated polyesters or vinyl esters. The major advantages are overall cost and ease of manufacture.

Engineering thermoplastics are traditionally used when conventional plastic parts are not strong or stiff enough for an application. The filter housing, depicted in Figure 21, is a pressurized part that was converted from non-reinforced nylon to 35% fiberglass filled nylon because it continued to be broken in use. It is a typical example of a part made with engineering fiberglass filled thermoplastics. When either through design analysis or from actual experience, the neat (non-reinforced) plastic is seen to not meet the strength or stiffness needed, fiberglass is often added to the plastic, thus improving the mechanical properties. The normal high-volume, high-speed manufacturing methods traditionally used for neat plastics can also be used for the composites, often with little modification in ether equipment or operating conditions.

Composite Markets

Composite materials are part of our everyday lives. We ride in cars and light rail systems with composite panels; we fly in planes with composite structures and storage bins; our homes have composite showers and numerous composite parts used in unseen places as parts of washers and dryers; and we enjoy recreation with composite skis, surfboards, and archery bows and arrows.

The breadth of the composites marketplace is seen in Figure 22. It is clear that composites use is spread across many market segments with no single segment dominating in the amount of material that is used. Somewhat surprising is the relatively small segment associated with aerospace.

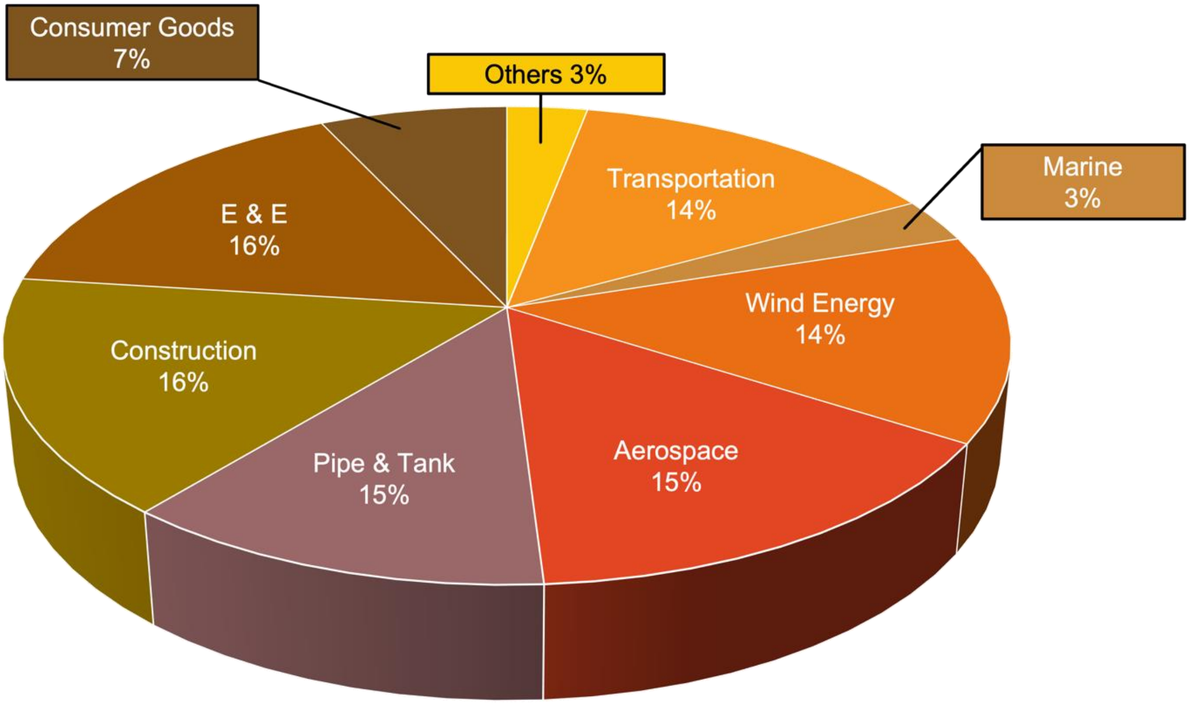


Figure 22 Markets for composites by weight shipped

Some of the categories might be surprising in their volume. For example, wind energy is almost as high as any other category. This shows the tremendous growth of wind turbines in which the blades are made of fiberglass composites with carbon fiber inserts for stiffness. Another surprising category is E & E (Electrical and Electronic). This reflects the high use of composites in circuit boards, electrical switches, motors, and other electrical control gear that has been made of fiber reinforced plastics for over a century. The relatively high value in transportation reflects the high use of fiberglass molding compounds in autos and not the use of carbon fiber composites—an application that is just developing. It is anticipated, however, that carbon fiber composites will eventually be a major structural material for automobiles and, of course, the transportation market will increase greatly when that occurs.

Another area that will likely grow for composites application is construction. Some installations have shown that when composites are wrapped around concrete columns that support bridges, the ability of the concrete to withstand earthquakes substantially improves. Wrapping concrete with composites also helps extend the life of the concrete as it reduces corrosion and helps prevent the flaking and splitting of concrete as it ages. Further construction applications include the construction of entire bridges using composite materials. Currently only foot and bicycle bridges or pedestrian bridges have been thoroughly proven, but the elimination of the need to continuously paint bridges made of steel and to continuously watch for corrosion are strong factors that will eventually lead to the creation of composite bridge structures for cars and trains.

Composites Supply Chain

The giants in the composite supply chain are the manufacturers of the fibers. The capital costs of the fiber making equipment, both for carbon fiber and for fiberglass, are very costly and the plants are highly automated and huge. Hence, there are only a few companies that make the fibers. These conditions are true for both carbon fiber and fiberglass.

The other group of large companies in the supply chain are the resin matrix producers. As with the fiber production, the capital costs are high and the plants are usually very large. However, there are also many small resin producers who focus on specialty resins that compete well in the marketplace.

A group of companies make a product called prepreg. This material is the combination of fibers and resin that ensures the proper amount of resin is added to the fibers. Many companies that mold composites prefer to buy prepreg rather than mix their own resin and apply it to the fibers.

Manufacturing equipment to make composite parts is usually made by medium-sized companies and sometimes by very small and highly innovative startups.

A small group of nation-wide suppliers of manufacturing consumable supplies has been developed to serve both the manufacturing giants and the small entrepreneurs. These suppliers sell the auxiliary materials that are needed to make composite parts. Examples of these materials are bagging film, mold release, hand tools, vacuum tubing, etc. The suppliers will also sell primary products like fibers and resins when the customer is not able to buy these products in quantities as large as is required by the makers of fibers and resin.

A host of other companies supply tooling, molds, and fixtures required for many of the manufacturing processes. There are also companies that specialize in machining composites (often required for after-molding trimming) and other finishing processes. Increasingly fibers in the form of woven goods or braided preforms are used to make composites. These fiber materials are often made by specialized fiber-processing companies.

When composites are put into service, some maintenance and repair are needed. For example, the military has large service centers that repair and do routine maintenance on equipment that contains composite parts. This equipment can be as extensive as an entire airplane. The civilian sector also has companies that do maintenance on composite parts, including, of course, the airline companies. There are also companies that specialize in aircraft repair and also teach repair to the airline companies and even to the military. These companies work closely with the FAA and DOD to ensure that the repairs meet the requirements of performance that were expected in the original parts.

Because the design and building of composites are so much more complicated than metals, several design and analysis specialists have arisen to help with design issues.

Each type of company in the supply can perform multiple services or processes and several of them do. However, most of the companies try to not compete with their customers.

Fun Activity

Objective: Discover the differences in the properties of composites and non-reinforced materials by examining their properties as obtained from a database.

Procedure: Using either a printed or electronic data base, compare the various physical properties (strength, modulus, coefficient of thermal expansion, etc.) for two thermoplastic plastics at three different levels of reinforcement. Compare the physical properties for two thermoset plastics at three different levels of reinforcement.

Overview and Transition

The first chapters of this book have presented the “big picture” of how composites have helped shape our modern world and the important role of composites in the future. Hopefully you have seen how composites are helping to meet national goals. We also looked at the history of composites, a brief explanation of the nature of composites, and an overview of the composite industry to help you get a foundation for these important materials.

Now, we will look more deeply into the nature of the fibers and the resins that make up composites in an effort to show you why composites are synergistic. That is, why combining fibers and resins results in properties that are greater than the properties of either of the components separately.

But this synergy must be carefully constructed. There are design concepts that need to be followed and these will be explained. I hope that the design concepts are presented in a way that is easy for you to understand.

Then, we will look at how to manufacture composites so that the designs are followed properly and the synergy can be realized in actual composite parts. We will also look at how to recycle composite waste and composite structures when they come to the end of their useful life.

After all this, I thought it would be useful to examine how you might plan your career in the composites field. Completing this book will, I hope, be a pleasant journey. Maybe you will find a career in composites.

Chapter 3 — Fibers (Reinforcements)

As most people already know, a fiber is a material that has a long axis (length) compared to the other axes (height and width). Fibers are usually circular or nearly circular so the height and width are often specified as a diameter. These dimensions are expressed scientifically using the term "aspect ratio" that is defined as the ratio of the length to the diameter.

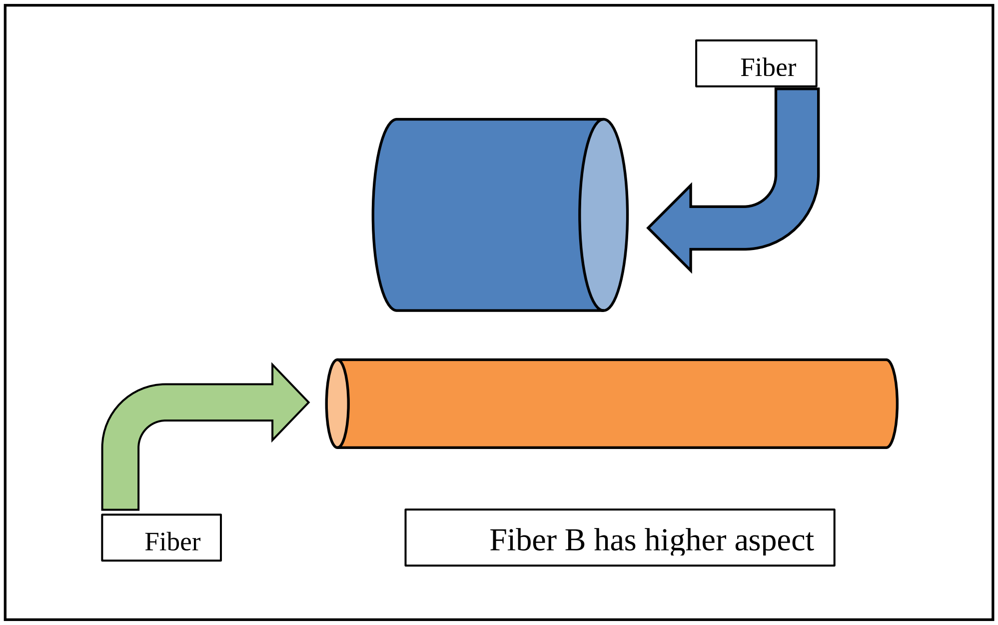


Figure 23 Aspect ratio diagram

Most of the fibers used to make composites have an aspect ratio of 20 or higher. Studies have shown that, in general, as the overall length of the fiber increases, the mechanical properties of a composite also increase. Therefore, the fibers used in high performance applications like airplane structures are continuous across the entire part. To facilitate the use of continuous fibers, most fibers are sold on spools (much like large spools of kite string). Even when the fibers are going to be chopped to shorter lengths to accommodate a particular manufacturing process, the use of spools of fibers is common.

Although many types of fibers are used in composites, three fiber types are dominant commercially and those are the ones focused on in this book. Those fibers—fiberglass, carbon or graphite fibers, and aramid (Kevlar™) fibers—are shown in Figure 24. They can be easily distinguished from each other by color. Fiberglass is white, carbon fiber is black, and aramid fibers are yellow. Each will be discussed in a section of this chapter.

Figure 24 The fiber types--fiberglass, carbon fiber, aramid fiber

Fiberglass

The raw materials to make fiberglass are silica sand and various additives like soda ash and limestone. Varying the additives will create different types of fiberglass. The most common fiberglass types for composites are E-glass (less costly) and S-glass (stronger). Because E-glass is strong enough for most applications employing fiberglass, the lower cost leads to E-glass being more widely used than S-glass except for some special applications

The process for making fiberglass is actually quite simple. The sand is melted at a very high temperature and the soda ash and limestone or other additives are added to the molten sand. The molten material is then pushed through a plate with dozens of very small holes in it. This makes many thin streams of glass that are quickly cooled to become fibers. The fibers are then gathered into bundles and wound onto spools. The bundles of fiberglass are called roving.

The number of filaments gathered into a bundle (roving) normally ranges from 200 to 1,200 depending on the number of holes through which the molten glass is pushed. A fiberglass bundle is shown in Figure 25 with the strands separated for illustration.

Figure 25 A fiberglass bundle (roving) that is separated to show the fibers

Historically natural fibers such as wool or cotton were made from short strands (called staple) that were typically 2 to 4 inches long. To make very long, continuous fiber threads that were needed to weave cloth, the staple fibers were twisted together using a process called spinning because the twisting was done with a spinning wheel. Today, any process for making fibers is still referred to as spinning, even though no spinning of the fibers is done. Hence, the step in the fiber making process where the molten glass is forced through the holes in a plate, is called the fiberglass spinning process.

The fibers are somewhat susceptible to mechanical damage in processes like weaving, knitting, braiding, or other handling steps that might be needed to make the final composite or other fiberglass product. To protect the fibers from damage, a very thin coating is applied to the fibers before they are wound onto spools for shipment. This protective coating is called a finish. Historically, cotton, wool, and other fibers were also coated with a thin protective layer, usually made of starch.

For fiberglass to be most effective in composites, the fibers must bond very strongly to the matrix resin. Sadly, the most common resins used as composite matrices with fiberglass do not bond well enough to the fibers for most applications. Therefore, fiberglass manufacturers coat the fibers a resin that bonds very well to both the fiberglass and also to the matrix. The coating materials link or couple the fibers to the matrix and are called a coupling agent.

Obviously, it would save time and money if the finish to protect the fibers and the coupling agent to help the fibers bond to the matrix resin could be the same substance. Fiberglass manufacturers have been successful in developing coatings that perform both the protecting and the bonding functions. However, since the matrix materials are often quite varied chemically, the sizings/finishes must also be chemically varied in order to couple properly. The development of effective coating materials to bond with each matrix is a difficult and time-consuming process. Therefore, the exact nature of these combination substances (still called sizings) is a closely guarded trade secret for most fiberglass companies.

One of the biggest applications of fiberglass composites is adding fiberglass as a reinforcement to common plastics in parts that are injection molded. In these applications the fiberglass is usually chopped and then added directly to the plastic by the plastic manufacturer. The resultant mixed plastic material is much stronger and stiffer than the non-reinforced plastic and the parts are made as they would have been made with non-reinforced plastics.

Fiberglass composites are also used when strength must be combined with electrical non-conductivity. Perhaps the best example is ladders used by electrical utilities and electricians. The ladders need to be strong, stiff, light weight, and non-conductive. Only fiberglass composites meet those criteria.

Carbon/Graphite Fibers

The demand for reinforcements that are stiffer and stronger than fiberglass led to the development of structural carbon fibers in the 1950s and 1960s. These fibers were initially made from rayon (a polymer derived from cellulose) and pitch (from oil and coal) but were soon overtaken in volume and most properties by fibers converted to carbon fibers from polyacrylonitrile (PAN) textile fibers. PAN is a synthetic polymer, commonly called Orlon, that is somewhat like nylon or polyester, and was being used to make fibers for sweaters and carpets.

The process for making carbon fiber from PAN fibers is more complex than the process for fiberglass because it involves two major steps: 1) Making the PAN fibers, and 2) Converting the PAN fibers to carbon fiber. Typically, these two steps are done in different locations.

Making PAN fibers begins with raw chemicals that are reacted to make the PAN polymer. The polymer is pushed through holes in a plate much like the molten glass in the fiberglass spinning process. The PAN fibers are cooled and gathered into bundles (called tows) that are then wound onto spools. As with fiberglass, the process for making the PAN fibers is called fiber spinning. The spools of PAN fibers are the starting materials for the next step in making carbon fibers.

The second major step in the carbon fiber process takes the strands of PAN fiber through a series of ovens where the fibers are oxidized so that they won't melt, carbonized where all the atoms except carbon are removed, and then graphitized where the remaining carbon atoms are forced to rearrange into a very strong and stiff molecular structure.

Carbon fiber manufacturers learned that by increasing the heat of the final oven and other changes in the process, fibers of almost pure carbon could be created and these fibers were stronger and stiffer than previous carbon fibers. Investigations revealed that the structure of these pure fibers was similar to graphite. Today, all carbon fibers are nearly pure carbon and the terms "carbon fiber" and "graphite fiber" are used interchangeably.

It is also possible to make carbon fibers starting with a material called pitch that can be derived from either oil or coal. The pitch (a solid material that is "pitch" black) is melted and then forced through holes in a plate in a typical fiber spinning process. The pitch fibers are then passed through ovens that are similar to those used in the second step in making carbon fibers. The production of carbon fibers by both the PAN and the pitch processes are illustrated in Figure 26.

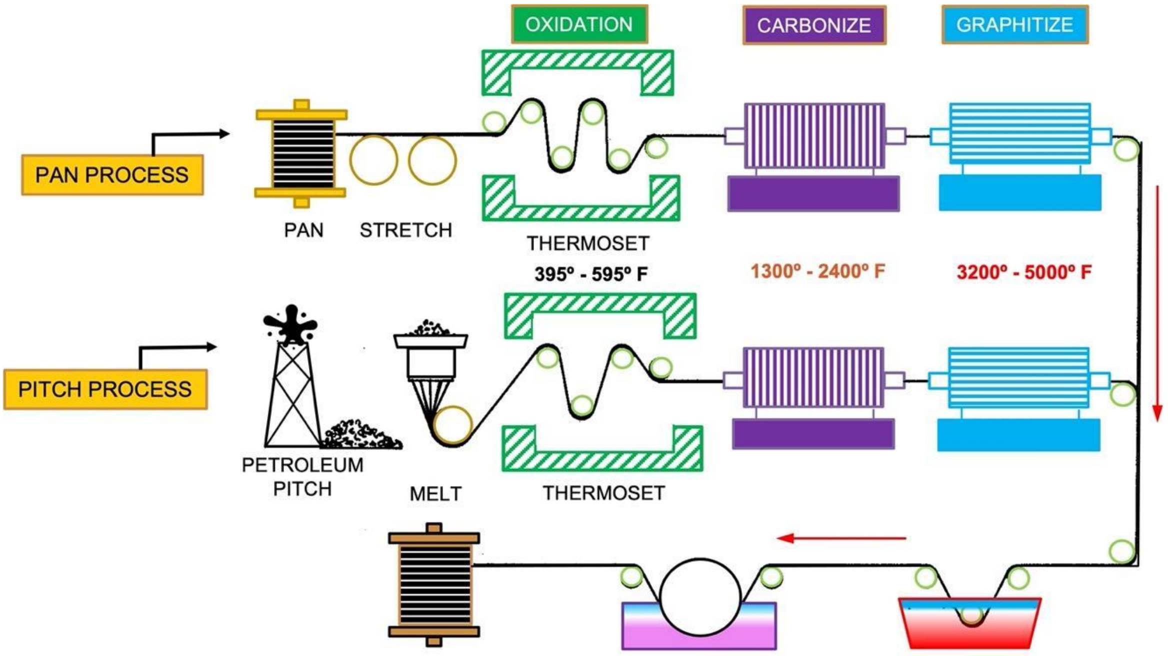


Figure 26 Making carbon fiber by the PAN process and the pitch process

Notice that the difference between the processes is at the beginning. The PAN process begins with preformed PAN fibers (on spools) that are stretched and passed through the ovens whereas pitch begins with a petroleum or coal byproduct that is melted and then passed through the ovens. In both cases, the fibers are surface treated and coated with a sizing before being wound on a spool.

The length of a production line to make carbon fiber is surprisingly long as is seen in Figure 27, a photo of actual carbon fiber lines showing the ovens. The capital costs for the huge ovens and other equipment are very high.

Figure 27 Photo of the ovens of two carbon fiber lines

During the PAN-based carbon fiber making process, some important changes occur in the fibers. These are summarized below.

- The weight of the fibers is reduced by 50%. Because the PAN fibers are sold by weight as are the carbon fibers, the reduction of weight means that the cost of carbon fibers is more than twice as much as the PAN fiber precursors, even with no addition of processing costs or other expenses.
- The density of the fibers increases from 1.03 g/cc to about 7.00 g/cc reflecting the tight molecular packing of the graphite structure.
- As expected, the strength of the carbon fiber is increased greatly over the original PAN fiber (about 17 times more). The stiffness is also increased greatly (about 33 times more). The elongation (stretch) is decreased from about 5 to 1.6%. This reflects an increase in brittleness of the carbon fiber and suggests one of the reasons that the matrix is needed to protect the fibers from impacts and other environmental phenomena.
- The fiber diameter is reduced from about 14 microns to 7.4 microns. The small size of these fibers can be appreciated by comparing them to a human hair as shown in Figure 28.

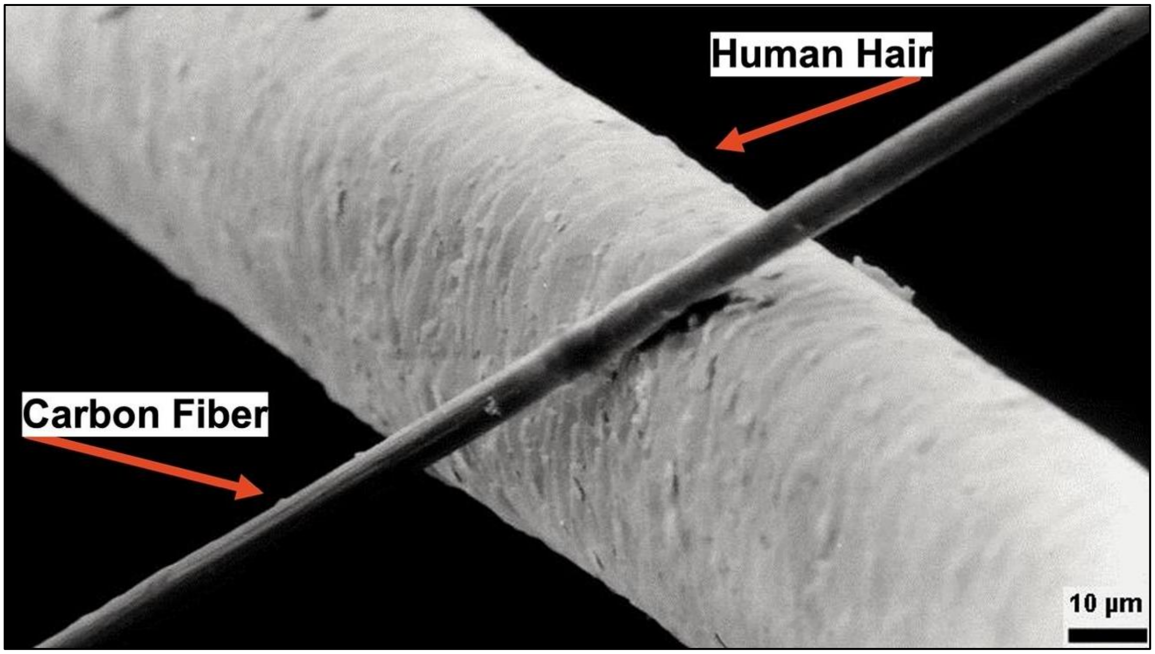


Figure 28 Comparison of human hair to carbon fiber

Throughout the PAN-based process, the individual bundles of fibers on the spools are moved through the process as a bundle, although the fibers are spread apart and the bundle flattened to ensure that all the fibers are uniformly heated. At the end, the same bundle is brought together and the fibers rewound. Therefore, each PAN fiber spool ends up as a carbon fiber spool at the end of the process. The bundles of carbon fiber are called "tows" and the number of filaments in a tow ranges from 1k (1000) to 340k. The smaller the tow count, the better the uniformity of heating and the better the uniformity of properties. However, small tows mean that the throughput in the process is lower and, consequently, the operating cost per fiber is higher. Therefore, a compromise is reached for each grade of carbon fiber. Aerospace grades usually range from 6 to 20k. Other grades can be made with as high as 100k. A photo of a carbon fiber tow that has been spread slightly is given in Figure 29.

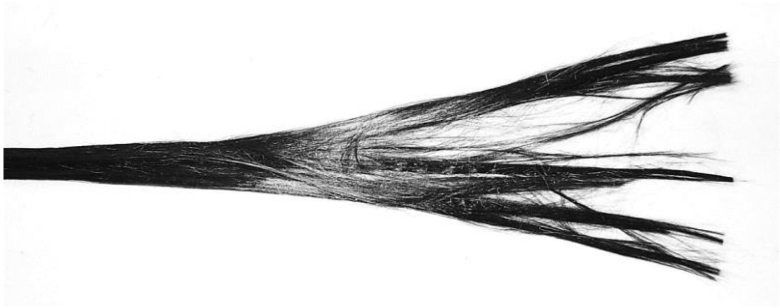


Figure 29 A spread tow of carbon fiber

Fibers made from pitch have an even higher stiffness than PAN-based fibers. In carbon fiber production different fiber properties can be achieved by varying the processing conditions to favor higher strength or higher stiffness.

The production of carbon fiber by the PAN process dominates the marketplace as shown in the accompanying chart.

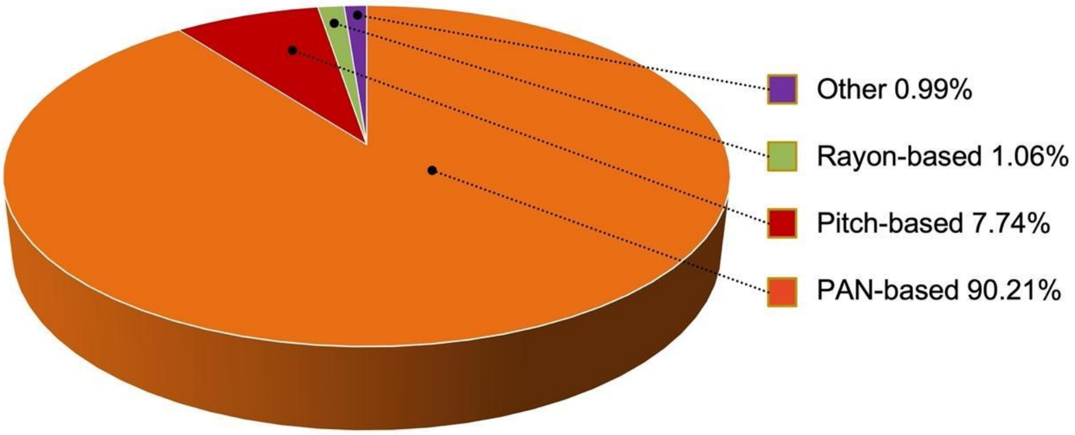


Figure 30 Carbon fiber production depending on precursor materials

Most of the applications of carbon fiber depend on the obvious advantages of high strength, high modulus, and low weight. Some of the most important of these applications include:

- Aircraft control surfaces (wings and tails) and, increasingly, full fuselages
- Helicopter rotor blades and bodies
- Wind turbine blade structural reinforcements
- Aircraft structural parts such as doors and landing gear assemblies
- Racing car bodies and frames
- Spacecraft, rockets, and missiles bodies
- Aircraft non-structural or semi-structural parts like luggage storage bins, wall panels, waste tanks, and cargo containers
- Skis and snowboards
- Artificial feet and legs

PAN-based carbon fibers are moderately good conductors of electricity and heat. However, pitch-based carbon fibers are among the best conductors of heat known, surpassing that of most metals. Also, most materials expand when they are heated, but carbon fibers either stay about the same or may even decrease slightly when heated. This feature makes carbon fiber composites ideal for applications where temperatures vary and the part needs to be constant in shape. Some applications that depend on thermal/electrical properties include:

- Space structures such as telescopes where the position of the mirrors and other equipment must remain fixed even though the temperatures vary from several hundred degrees above zero to several hundred degrees below zero as the telescope goes around the earth and is shaded or not from the sun

- Heat shields (thermal protection systems) for missiles and rockets
- Aircraft brakes
- Rocket exhaust nozzles
- Housings for computers, small motors, and electrical control panels where the heat must be dissipated away from the electronic circuits
- Shields against electrical interference (when coated with metal)

When structures made of carbon fiber composites are in a crash, the fibers break individually and absorb, in total, an extraordinary amount of energy. Therefore, composites are increasingly finding applications in crashworthiness. Carbon composites will also dissipate energy through damping processes where they interact with the matrix. This gives excellent acoustic properties.

- Automobile frames
- Musical instruments
- Audio speakers
- Rollers for industrial processing such as in the paper industry

Applications based on biological inertness and X-ray transparency include

- Artificial joints
- Heart-valve components
- X-ray tables and mounting arms

Composites have excellent fatigue failure resistance, that is, they can be flexed over many (millions) of cycles with little or no change in properties.

- Artificial feet and limbs
- Compressor blades
- Textile machine components

Most of these applications are growing rapidly and suggest a bright further for the carbon fiber composites market.

Aramid (Kevlar®) Fibers

Aramid is the generic name for a group of fibers based on a polymer first developed with the trade name of Kevlar®. Other aramids are available but the DuPont product dominates the market. The fiber was originally developed as a reinforcement for tires to compete with steel fibers, but that application did not gain wide market acceptance and so other applications were sought. Two major applications have been developed. Those are 1) A protection for people as bullet proof shields and body armor and 2) Protection against debris for key areas on airplanes, rocket motors, and other high-performance products.

The manufacturing process for aramids is similar to the process for making many other synthetic fibers such as PAN and fiberglass. In the aramid process the polymer is made by mixing the proper starting materials which then react to form a polymer. The polymer is then filtered and washed and dissolved in a solution. This is required because the nature of the polymer makes melting it difficult. The polymer solution is then forced through a plate with holes (a spinneret) in a typical synthetic fiber spinning process. The fibers are washed, dried, and wound on spools.

The strength and modulus of aramids lie between those for fiberglass and carbon fiber but the density of aramids is less than either carbon fibers or fiberglass so it is lighter weight. Also, the impact toughness of aramids is higher than carbon fiber and about the same as fiberglass. Therefore, the combination of good strength and stiffness, high impact strength, and low density (low weight) means that aramids are the best high-performance fiber for resisting impact damage. This is shown in Figure 31 where a pressure vessel is impacted repeatedly at various energies and the retention of the original strength is measured. You might imagine how important this could be with a pressure vessel in your car (say if your car was fueled by natural gas or hydrogen) and you were in an accident.

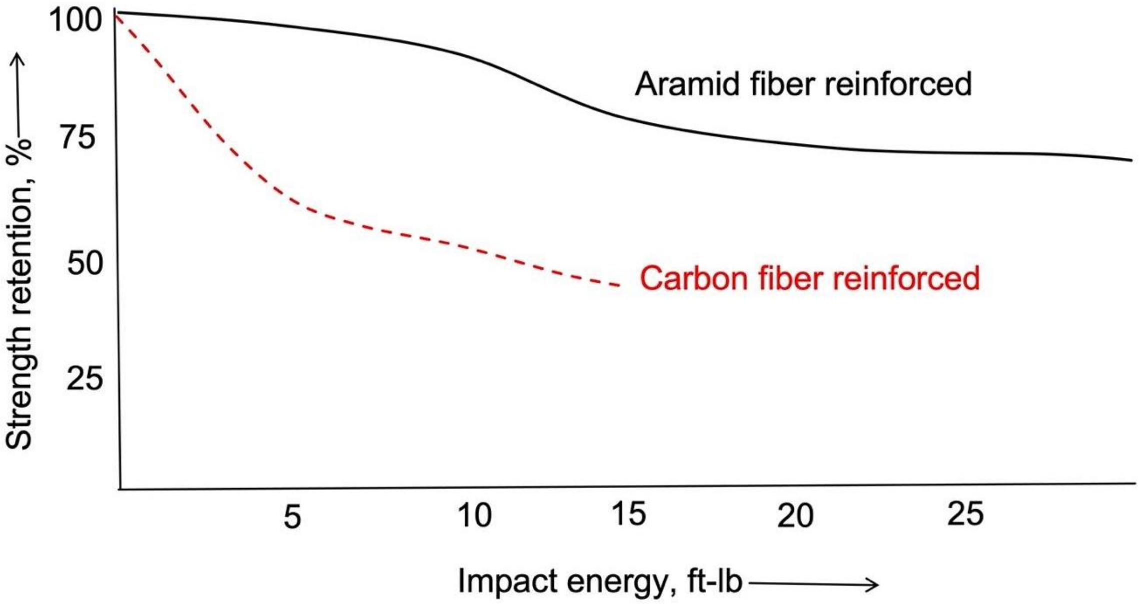


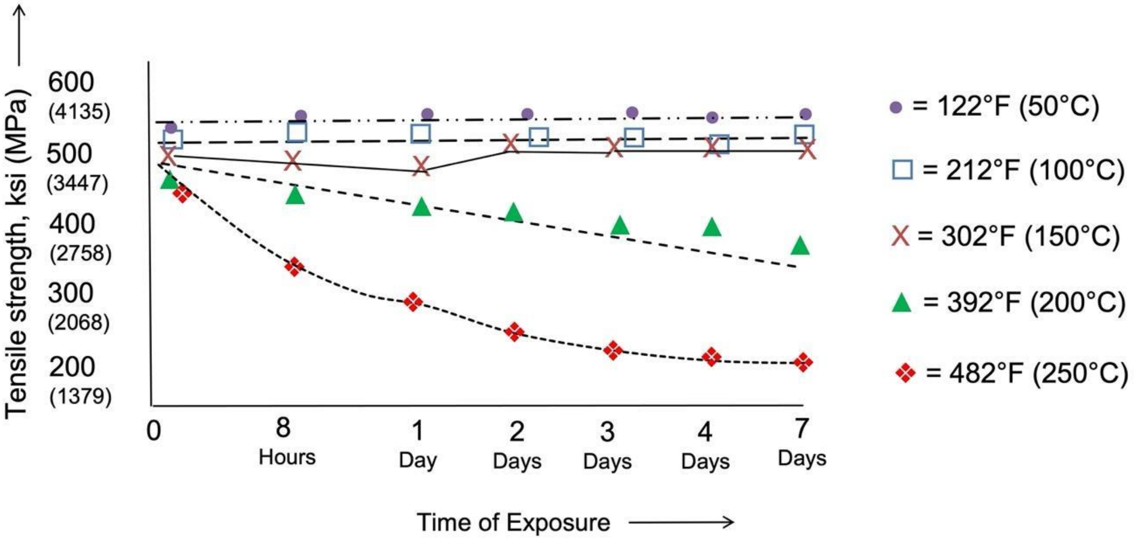
Figure 31 Aramid versus carbon fiber composites impact resistance

This high resistance to impact damage has led to aramids being used as protective layers in rocket motor casings (where impacts from debris can be a problem) and on the of airplane underside of wings where rocks and other debris might be flipped upward against the wings during landing or takeoff. Aramid fibers might also be placed on the leading edge of wings as a protection against bird strikes.

The ability to withstand impacts is also important for body armor (bullet proof vests), helmets, and ballistic shields. Again, the combination of impact resistance and light weight makes aramids an important choice for these applications. Not only do the aramid fibers resist breaking when struck by a bullet, they transfer impact energy sidewards, along the length of the fibers, better than carbon or fiberglass. This sideways transfer means that less force is directed straight through the shield onto the body of the person and would help prevent breaking ribs and similar body damage.

A disadvantage of aramids when compared to carbon fibers and fiberglass is resistance to heat. Both carbon fibers and fiberglass are much more resistant to high temperatures than aramids. The decay of strength for aramids with increasing temperature over time is shown in the following figure. Clearly aramids should not be used in environments where the temperature is over 300ºF if strength is to be retained. For most applications near room temperature, or even as high as boiling water, the properties of aramids do not appreciably change.

Figure 32 Temperature effects on aramid fibers



Aramid fibers are resistant to most chemicals with over 90% retention of strength, but some caution should be taken when aramids are in contact with nitric and hydrochloric acids. Sulfuric acid dissolves aramids and, therefore, should be avoided.

Other Fibers

Natural Fibers

Some composite manufacturers would like to use natural fibers in order to be more environmentally conscious. The most common natural fibers used in composites are jute, sisal, kenaf, palm, and pineapple. Other common natural fibers like cotton and wool are not strong enough to be used for commercial composites. Even those natural fibers most commonly used in composites have strengths that are significantly lower than fiberglass, aramid, and carbon fibers.

The costs of natural fibers are generally lower than the costs for synthetic fibers. This is especially true in countries where the synthetic fibers are imported and the natural fibers are locally grown and processed. Of course, the appeal of natural fibers is that they are renewable. However, because they are natural, the variability in properties can be quite significant. The general position of natural fibers versus synthetic fibers and fillers (particles) is shown in Figure 33.

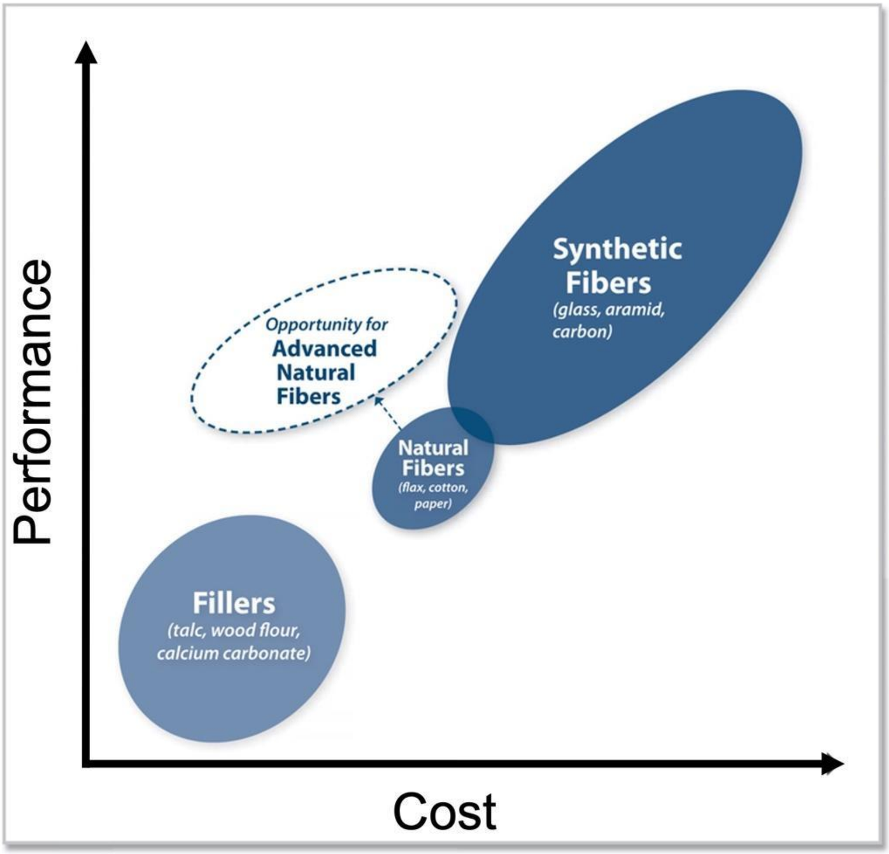


Figure 33 Cost-performance chart for fibers and fillers

Despite these disadvantages, the environmental appeal of natural fibers and the economic and political advantages of using products from developing countries are major factors for some companies and these fibers could become a significant factor in markets such as sporting goods, outdoor products, and automobiles, mostly as a replacement for fiberglass.

Ceramic Fibers

These very rigid and high-melting fibers are important as reinforcements for composites to be operated under very high temperatures or other extreme conditions. In these applications the ceramic fibers are generally used with a matrix that is also suited to extreme conditions—usually a metal, ceramic, or charred carbon. The use of ceramic fibers in armor for tanks and other vehicles is an interesting application because the fibers help stop the growth of cracks in the composite matrix, thus preventing penetration of projectiles.

The most common of these ceramic fibers is silicon carbide (SiC). These fibers are generally very short (about the length of whiskers). A major application is to add these materials to a hard steel or other strong metal to be used as cutting tools in metalworking operations. The addition of the silicon carbide gives greater strength and toughness to the cutting tool, thus extending its life.

Silicon carbide can also be made in a continuous form by coating the silicon carbide onto carbon fiber. This combination allows the ceramic properties to be enjoyed along with the ease of manufacturing the composite that comes with continuous fibers. Major applications to be developed are aerospace vehicles used under extreme conditions such as hypersonic rockets and missiles.

Ultra-high Molecular Weight Polyethylene (UHMWPE)

Another type of fiber having unique and useful properties is made by modifying the process of making polyethylene, the most common plastic in the world that has thousands of uses. The modification of the standard process results in a dramatic increase in the molecular weight of the polyethylene. This is done by lengthening the polymer chains. When that is done, the polymer can no longer be easily melted and must be processed by other methods, usually by pressure molding heated sheets of the material. The very long molecules are excellent impact absorbers and, therefore, UHMWPE has become a competitive material for making bullet proof vests and shields. Not only is the impact resistance good, but the weight of the PE is the lowest of any plastic, thus helping to reduce the weight of the ballistic prevention products.

While excellent for impact resistance in the moderate temperature conditions expected for human use, UHMWPE cannot be used in high temperature environments (about the temperature of boiling water). Moreover, the strength and modulus are far below the levels needed for high performance applications. But applications operating near room temperature, especially where impact resistance and/or weight savings are important, are growing for this material.

Reinforcement Forms

Although the fiber manufacturers generally sell the fibers in continuous-fiber spools, many companies that make composite parts prefer to use the fibers in other forms. This conversion of the fibers from long, continuous strands to another form is usually done by separate companies or separate divisions that specialize in making these alternate fiber forms. As each fiber form is discussed, some advantages and disadvantages of that form will be mentioned along with types of products that are commonly made using that form.

Woven Fabrics

Historically the most useful form of any fibers (like wool and cotton) is to weave them into fabric, sometimes called cloth, textiles, or broad goods. The common reinforcement fibers for composites—fiberglass, carbon, and aramid—can also be woven into fabrics. In the weaving process continuous fibers are aligned on a loom in such a way that the fibers can be advanced through the loom as the cloth is produced. These fibers are said to be in the machine direction and are called the warp. The loom provides a way for other fibers to be interwoven above and below the warp fibers in a crossing manner. These interwoven crossing fibers are called the weft, woof, or fill and the crossing direction is called the transverse direction. It is also possible to have fibers that are placed diagonally across the warp. This direction is called the bias.

The simplest weaving pattern is for the crossing fibers to go over and then under the machine direction fibers in an alternating pattern. This is called a plain weave. It is illustrated in Figure 34. Other weaves are illustrated in the figure and show that in some cases more than one weft fiber can cross more than one warp fiber in a variety of patterns. Some of the weave patterns are quite tight (stiff) while others are softer and have a greater ability to conform to shapes on which the fabric is placed. (Satin, for example, is highly conformable, that is, it drapes easily, whereas plain weave is quite stiff.)

Plain weave has the advantage over other weave patterns in that the fibers are relatively fixed in position and do not move during handling and molding. However, when striving for the ultimate mechanical properties, all woven products, but especially plain weave, have crossover points where the fibers cross each other. These crossovers are potential weakness points because the fibers can be pressed against each other and cause fiber breakage.

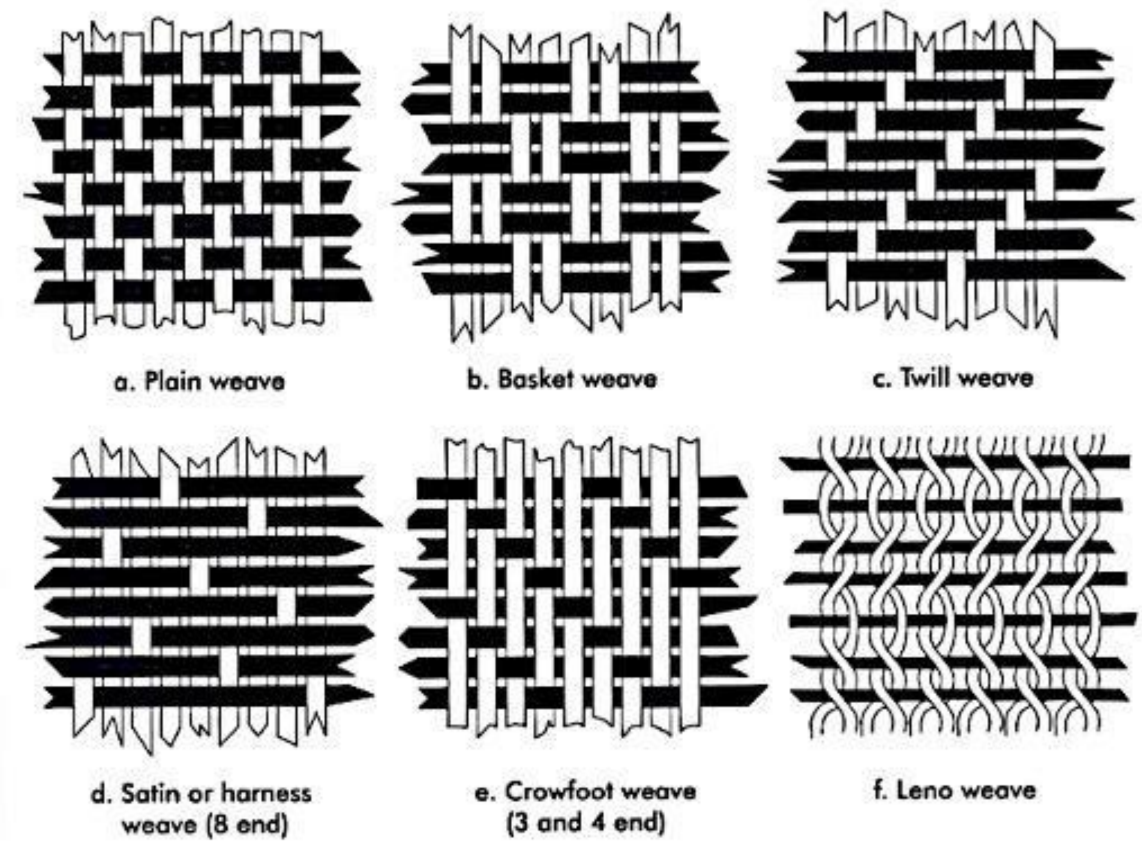


Figure 34 Weave patterns

In addition to the weave pattern, fabric properties can also depend upon parameters like areal weight (weight per square foot), fabric thickness, thread counts (number of threads per inch), fiber diameters, and the possibility of mixing fiber types in a single fabric. This large number of options gives an incredible variety of fabrics that can be made. Therefore, extensive lists of fabrics by various categories and style numbers are published to assist users in obtaining the type of fabric desired.

The wide variety of fabrics can be illustrated by mentioning two fiberglass fabrics used widely in composites—one thin and the other thick. The thin fabric is called veil. It is comprised of a simple, tight, plain weave made from fine strands so that it creates a fine, uniform fabric. Veil is often applied just under the surface of a fiberglass part to mask the underlying composite material and give a smooth outer surface. It also serves as a physical barrier to fiberglass strands from underlying layers that may become prominent (that is, they poke upwards) because of the natural movements of the composite.

The thick fabric is called woven roving. It is simply a large-count (many strands) fiber bundle that is loosely woven into one of the patterns discussed previously. The looseness is needed to ensure proper wet-out of the fibers. This material is used when a rapid buildup of reinforcement weight is desired. This can occur when an area of the composite part needs special reinforcement because it is subject to high stresses.

Non-Wovens

Not all composite products need the strength and stiffness that comes from woven fabrics in which the fibers are continuous. For example, a manufacturer of boats may be currently using chopped fiber spray-up (discussed in a later chapter) but would like the convenience of a sheet reinforcement or a design for the reinforcement may specify that the fibers be randomly oriented. These fiber forms can be easily achieved by using non-woven materials.

The most common non-woven form is called chopped strand mat. (A mat is simply a sheet of fibers that are randomly laid down.) Chopped strand mat is made by chopping fiberglass strands onto a belt to the thickness desired and then spraying on a light binder to hold the fibers loosely in place. A chopped strand mat is shown in the Figure 35 (left side).

Figure 35 Chopped strand mat (left) and continuous strand mat (right)

Some applications require slightly better properties than can be obtained with chopped strand mat but may not need the properties or cannot bear the costs of a woven fabric. A product that fits this niche is continuous strand mat. It looks similar to the chopped mat but is made by swirling continuous fibers onto a belt and then spraying with a binder. The longer fibers give better mechanical properties than chopped mat and the continuous product is easier to handle. (See Figure 35 on the right side.)

Because of the high costs of carbon and aramid fibers, these fibers are generally only used when maximum properties are desired and, therefore, have not been traditionally used to make mat products. However, when carbon fibers are recycled (as discussed in a later chapter), many recycling processes require that the carbon fibers be chopped. Then, after the resin matrix has been removed, the chopped carbon fibers are conveniently made into mats. These mats are not generally sold for structural products but have wide application for semi-structural uses like cases for computers and other products where the strength and look of carbon fibers is important but ultimate mechanical properties are not needed.

Prepregs

If a company making composite parts wants to use continuous fibers but doesn't want the somewhat difficult task of applying the resin to the fibers, the solution is to use prepreg. The companies making prepreg buy the fibers, apply the resin of choice, and sell the combined fiber and resin. This combined product is called prepreg, a name that means "preimpregnated fibers". Prepreg is usually sold as a sheet material that is made by spreading several tows of fiber so that they are a single fiber thick and laying these spread tows next to each other to make a sheet of whatever width the customer wants, but usually no more than 5 feet wide. Then resin is precisely applied to the sheet of dry fibers. This can be done with a doctor blade that spreads the resin/matrix evenly on the fibers but can also be done by coating the resin onto a large roller that applies the resin as the fiber sheet passes under the roller. The resin and fibers are then passed through an oven where the resin is heated to be a thin liquid and is pressed into the fibers to ensure that all the fibers are completely coated. (The heating is not high enough to cause the resin to cure.) Release paper is then applied so that the continuous sheet can be rolled up without sticking to previous layers. This process is illustrated in Figure 36.

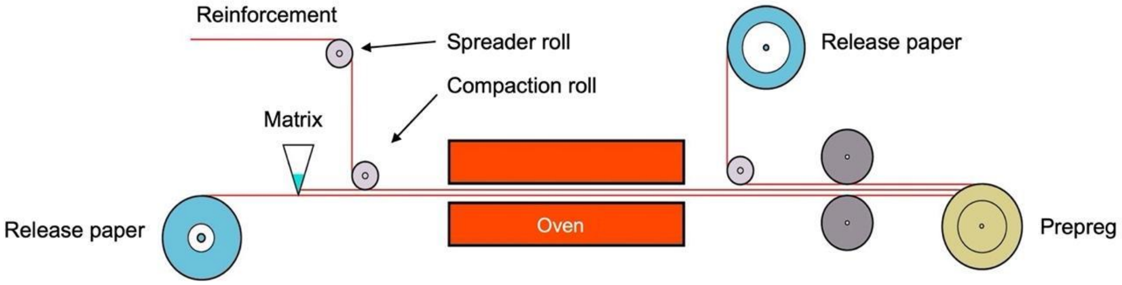


Figure 36 Diagram for making prepreg

When the prepreg is made with spooled fiber, the fibers are all aligned in the long direction, ideally with no gaps between the fibers. This material is called unidirectional prepreg and is shown in Figure 37.

Figure 37 Unidirectional prepreg

Unidirectional prepreg is the material most commonly used by aerospace companies because it gives the advantages of continuous fiber, allows the composite part molder to orient the fibers as desired (more on this in the chapter on design), and has a precisely controlled resin content and resin coating all of the fibers.

Some composite molders prefer fabrics to unidirectional fibers and these fabrics can be and are made into prepregs. Prepregs can also be made with tow (strands of carbon fiber), especially when used in machines that lay the fibers into the mold automatically. These machines are discussed in a later chapter.

A disadvantage of using prepreg is that the resin is ready to be cured (discussed in the chapter on resins) and that means that the curing reaction is proceeding. To slow the reaction and prevent premature hardening of the prepreg, perhaps while it is still being stored waiting to be used, the prepreg must be kept cold. Most prepreg manufacturers suggest that the prepreg be stored at 0ºF until it is to be used. Even when stored at these conditions, the prepreg will continue to cure and therefore has a limited storage life, usually about 6 months.

Three-dimensional Forms

An irony (and difficulty) of making composite products is that the products are usually three-dimensional but the raw materials (reinforcements) used to make them are generally one-dimensional (fibers) or two-dimensional (fabrics, mats, and prepregs). Therefore, in making composite parts, a designer must be able to envision three-dimensional products from two-dimensional raw materials. Thus, reinforcements are layered and/or turned upward to give vertical shapes to get three-dimensional products. Such techniques are often difficult and usually require manual placement of the fiber sheets. Thankfully, some of the raw material suppliers have been inventive in the forms they supply and have made some of the dimensional conversion to supply products that are nearly full three-dimensional. Some of the methods to create three-dimensional products will be discussed later in this book.

Braiding the fibers is a technique that is growing in popularity as a way to achieve a three-dimensional structure. This ancient technique has been adopted to create preforms, that is, fibers that have been formed into the shape of the final product (or nearly so) but have not yet had the resin matrix added. The dry preform is placed into the mold, then the molder applies the resin, and then cures the part. This technique gives a three-dimensional product with little hand labor. Some of the composite parts that use braided preforms are hockey sticks, prosthetics, aircraft horizontal stabilizers, and bicycle frames. Figure 38 shows some braided preforms.

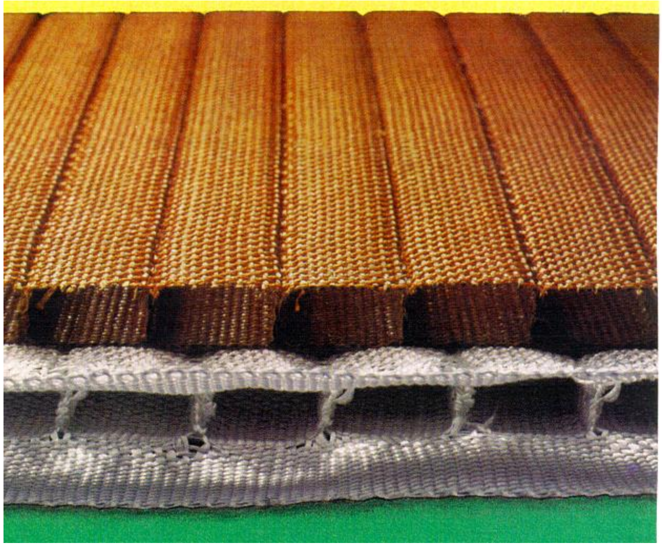


Figure 38 Braided preforms

Preforms can also be made by chopping fibers and blowing them over a shaped screen and then spraying with a binder to hold the fibers in place. Alternately, fiber mat could be pressed over a mold to give it some three-dimensional character.

Another method of creating a three-dimensional material is to stitch vertically through a two-dimensional layered structure. While the three-dimensional strength may not be high (depending on the number of stitches and the type of stitching fiber), the layered structure is held together and the vertical stitches transfer some of the applied loads between the layers to give additional strength and stiffness.

Fun Activity

Objective: Determine the relative wet-out characteristics of open and tight fabrics.

Procedure:

1. Make two lay-ups using fabrics that are vastly different in openness. The lay-ups should be at least four layers thick.
2. Place the lay-ups over a container and then clamp the edges of the reinforcement assemblies so they do not move.
3. Pour a set amount of resin, such as 300 ml, into the middle of the reinforcement assembly so that the resin flows through it and then into the container. (If preferred, corn syrup or motor oil can be used in place of the resin.)
4. Time the flow of the resin through the reinforcement assembly. (If preferred, the container into which the liquid flows can be calibrated and the timing measured as the time to reach a certain volume in the container.)
5. Discuss the flow rate versus the openness of the fabrics.

Chapter 4 — Resins (Matrix)

Very few people working in the composites industry understand the nature of the resin matrices that are a main material, along with fibers, in composites. While resin chemistry can be quite involved, knowledge of a few basic concepts and some easy-to-understand principles will enlighten this important part of composites. This chapter will present those basic concepts and principles and will then apply them to the resins that are most commonly used as matrices in composites. This knowledge will result in advantages in the workforce and an improved overall understanding of composites for those who take time to read this material.

Basic Resin Concepts

Atoms (elements of the periodic table) are the basic units of chemistry and are the building blocks of all matter. Each atom has a nucleus with a unique number of protons, neutrons, and surrounding electrons. Two or more atoms can be combined to create molecules with each kind of molecule having different characteristics. Since any number of atoms can be combined to make these different molecules, the variety of possible molecules is infinite.

Resins are very long molecules and are made up of many atomic units (a few atoms that form a group with particular properties). When linked together, the atomic units form a chain-like material. (Like people holding hands, one to another.) Each link in the chain is an atomic unit and is called a monomer (which means “one unit”). When put together in a chain, the entire chain is called a polymer (which means “many units”). Some polymer chains can have several thousand atomic units (links) while other polymers might have just a few.

The term “resin” refers to polymers that are not yet in their final form and shape. After they have been molded or shaped, they are called plastics (from the Greek word for molded) although, in the case of composites, they are often called the matrix. Some composites, especially those with only a moderate amount of fiberglass reinforcement, are called FRP (fiberglass reinforced plastics).

Resins can be either liquids or solids as shown in Figure 39. The solids are often sold as small pellets so that they can be transported into and through manufacturing plant conveying systems and into the molding equipment with ease.

Figure 39 Resins can be liquids or solids

As previously mentioned, the matrix (resin) properties add to the reinforcement properties to create synergistic materials. The most important matrix property requirements include the following:

- Being moldable and, after molding, to hold its shape
- Protect the fibers from being damaged by environmental factors such as impacts, high temperatures, solvents, weather, and fire
- Being able to transfer an imposed load or force onto the fibers by bonding to the fibers and being stiff enough to push against the fibers when a force pushes against the matrix

The ability of a resin to meet these requirements depends to a large extent on the shape of the polymer chain. The chain of a resin could be very smooth and flexible, like a snake, or it might be highly branched and diverse like a tree. It could also be rigid like a board. These shapes result in polymers that are highly flexible (snake-like), stiff (tree-like), and strong (board-like).

Resin Principles

Chain Length Principle

The matrix of a composite consists of millions of polymer chains. If the matrix is a liquid, as it is before it is molded, these chains can move around each other and become entangled. As the liquid is cooled and becomes a solid, the ability for the chains to move is decreased and the chains remain entangled. When a tensile (that is, pulling) force, is applied to the matrix, the polymers try to slide apart but the entanglement makes that sliding difficult. If the entanglement is greater, the resistance to sliding is also greater. This is seen as an increase in tensile strength of the matrix. The same resistance to movement is seen for other forces like bending and pressing. Since having longer chains increases entanglement, we can say that increases in molecular chain length cause increases in mechanical strength.

Thinking of a plate of spaghetti might help in visualizing this situation. If the spaghetti strands are very long, the ability to wind them onto a fork becomes more difficult.

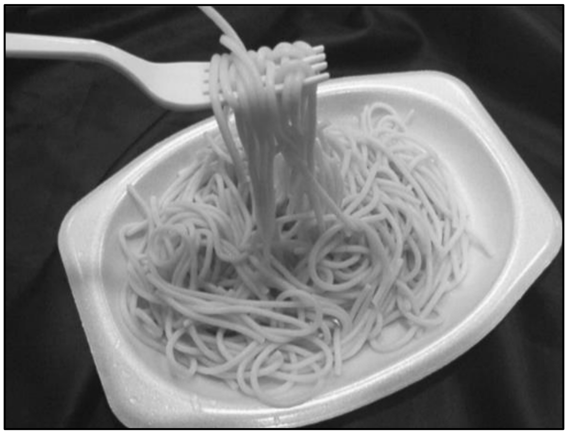


Figure 40 Spaghetti as an analogy for polymer chains

When heat is added to a solid polymer mass, the molecules gain energy and attempt to move. Initially this movement is just minor vibrating of the atoms in place. We can measure the movement of the molecules as an increase in temperature. As the amount of heat increases the movements become greater, sometimes with several atoms moving together, and the temperature increases further. This concerted movement can eventually lead to disentanglement of the molecules as additional heat is added. At some point, there is sufficient movement that the molecules are free to move independently and the polymer mass has melted. Of course, if the polymer chains are longer, the amount of heat to disentangle is greater. Therefore, increased molecular weight increases the melting temperature.

With this brief explanation, the molecular weight principle can be stated as follows: **Increases in molecular weight (length of a polymer chain) result in increases in most mechanical (like strength and stiffness) properties and thermal properties (like melting point).**

Some polymer chains have large attachments to the main backbone of the chain. The attachments to the chain are like barbs on barbed wire. These attachments prevent other chains from getting close and also prevent the polymer chains from sliding past each other easily. The difficulty of polymers to slide past each other increases the strength of the polymers when subjected to a pulling force as the barbs catch on each other. (This is discussed further when the chain shape principle is presented.)

Reactive Sites Principle

The atoms in a polymer molecule are held together because every pair of atoms share a pair of electrons that circle the nuclei of the atoms and prevent them from moving apart. These shared electrons create a covalent bond. However, the electrons are not necessarily shared equally between the atoms nor are they necessarily uniformly distributed along the chain. These situations create reactive sites on the polymer that are important in sythesizing the polymer and, of special importance for composites, are sites where reactions occur during curing of the resin. (Not all reactive sites are places where crosslinking can occur.) Two different types of sites are of particular interest in polymer reactivity where crosslinking can occur.

- Presence of a double bond between atoms
- Presence of a region of high electron density

Double bonds are areas where four electrons are shared by two atoms and are, of course, richer in electrons than normal bonds (where only two electrons exist). These double-bond areas are susceptible to chemical attack by molecules or atoms that are deficient in electrons. This will be discussed in greater detail later in this chapter.

The second type of reactive site usually involves the presence of oxygen (O), nitrogen (N), fluorine (F), chlorine (Cl), or bromine (Br) bonded to some other atom, usually carbon. These atoms are called electronegative atoms because they usually draw electrons from the other atom they are bonded to. When this occurs, the electrons spend more time around the electronegative atom than around the other atom. Note that some sharing is still maintained so the bond is still covalent. See Figure 41.

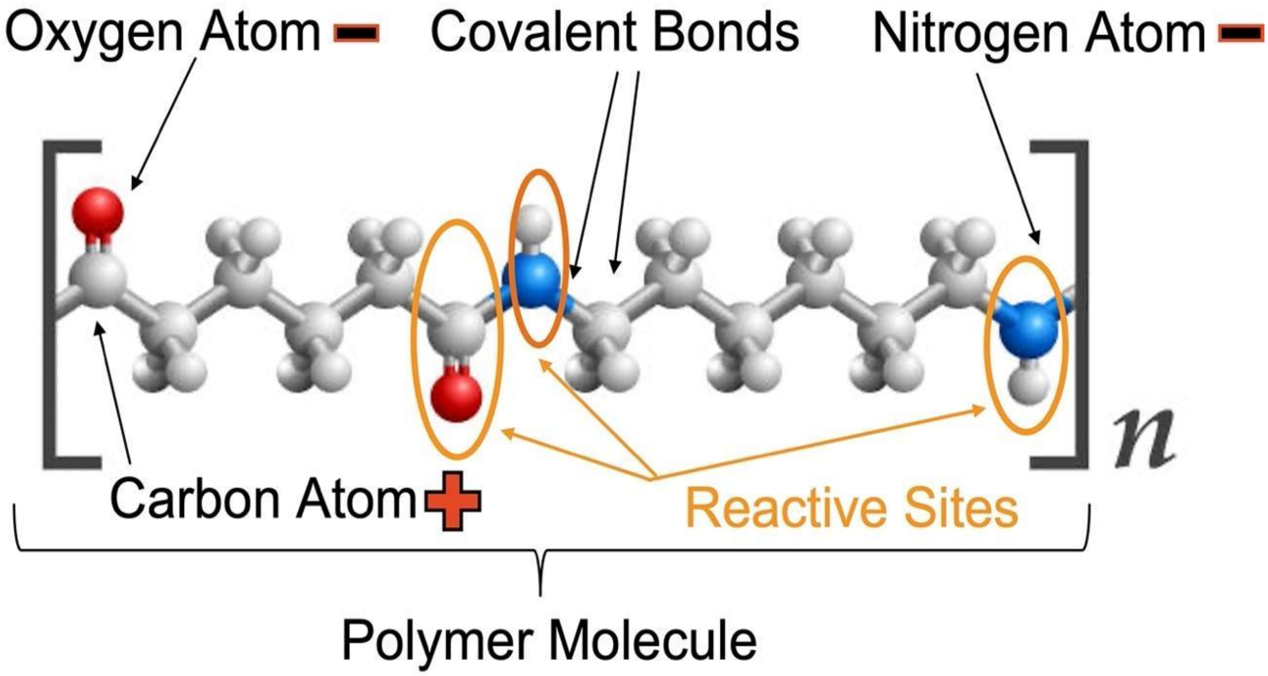


Figure 41 Polymer molecule illustration showing reactive sites

Some people prefer to think of the electrons in a bond as a cloud between and around the atoms. When one atom is electronegative, the cloud is larger around the electronegative atom. The other atom has less electron presence and becomes slightly positively charged. Another way to envision this electron sharing is to think of two people in bed and the electron cloud is the blanket that covers them. If one person rolls over and pulls the blanket, that person will get warmer while the other person gets colder. They still share the blanket, but not evenly.

Reactive sites can be built into the polymer and allow reactions to occur that can change the nature of the polymer molecule. Chemical reactions occur when electrons transfer from one atom to another, forming a totally new bond. When electron density is increased, the possibility of an electron transfer (reaction) is increased.

Crosslinking Principle

Some reactive sites are readily reacted by different active sites, somewhat like a lock that is opened by a particular key. When certain chemicals, called hardeners or co-reactants, are added to polymers containing the active sites, reactions can occur between the active sites on the polymer and the unlocking active sites on the hardener. If the hardener has an active site on both ends, that second unlocking active site can react with and form a bond at the active sites on another polymer. The hardener/co-reactant forms a link or bridge between the two polymer chains. This is called crosslinking.

When crosslinking happens, the length of the first polymer chain is increased because it now has the second chain joined to it. They are then a single chain but with twice the polymer chain length, plus the weight of the hardener bridge, that is, over twice the number of total atoms in one continuous chain. Of course, the weight of the first polymer chain is also increased by the weight of the second polymer and the bridge.

After much crosslinking has occurred, essentially all the polymers are tied together in a network, much like the strands of a spider web are tied together. (Figure 42) This results in a very high polymer chain length (the combined length of all the strands) and a very high average molecular weight because the polymers are then parts of a network.

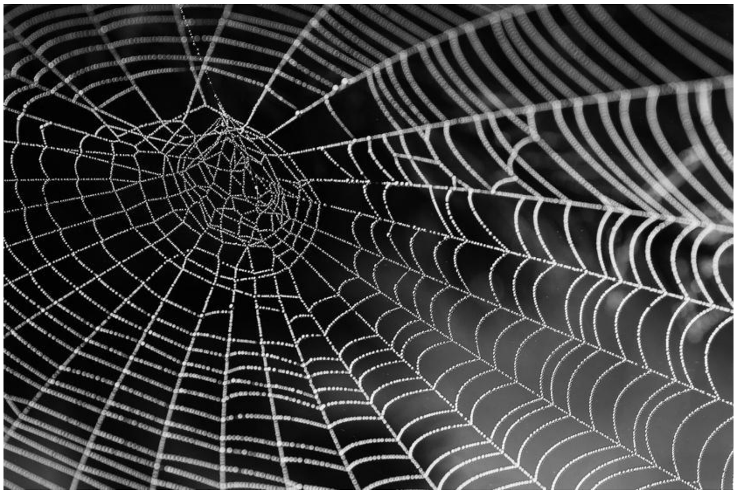


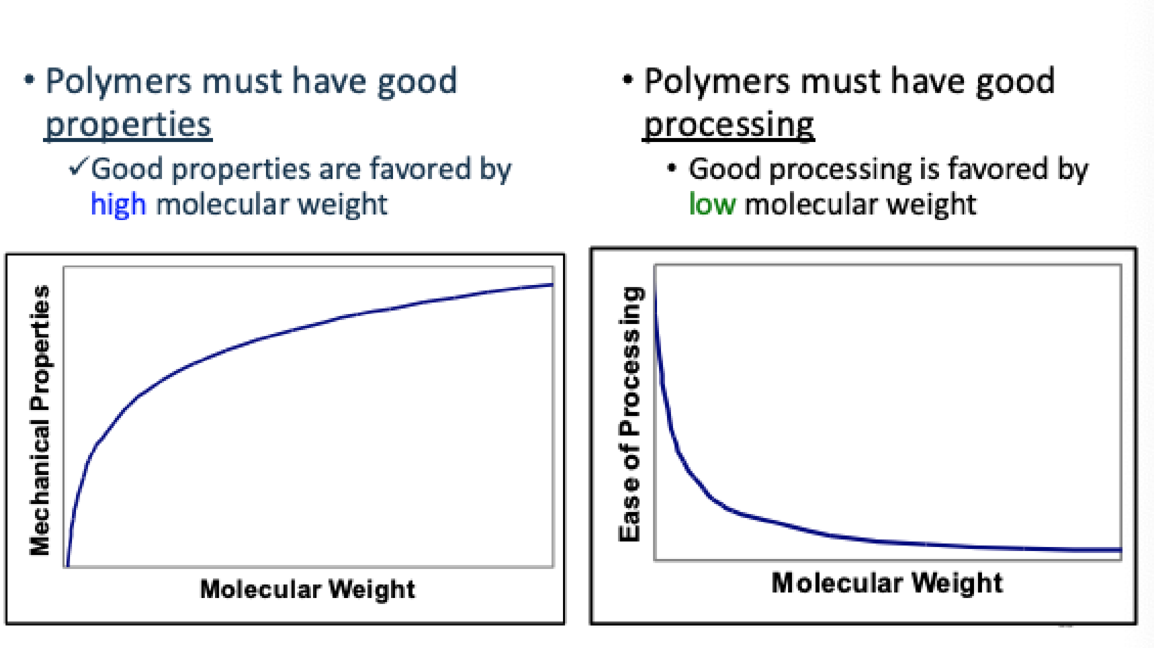
Figure 42 Analogy: Spider building a web by crosslinking the strands

From the chain length principle, it follows that both the mechanical properties and the thermal properties increase after crosslinking. The thermal effect of crosslinking is very important. Because molecules that are to be crosslinked often have many active sites on each molecule, the crosslinking can involve many molecules and the result can be huge increases in chain length (molecular weight).

The crosslinking principle is that reactive sites can be "unlocked" by hardeners/co-reactants and new bonds are formed. When the same hardener has multiple unlocking active sites, it can form a bridge between two or more polymers.

Thermoplastics and Thermosets

A dilemma in polymers exists because of the mechanical and thermal natures of polymer chains. This dilemma is illustrated in Figure 43. As previously discussed, the mechanical properties increase as molecular weight increases. However, ease of processing polymers is best done when the polymer can be easily melted and that is facilitated by low molecular weight. So, should the molecular weight be high or low? That is the dilemma.



- Polymers must have good <u>properties</u>
  - ✓Good properties are favored by high molecular weight
- Polymers must have good <u>processing</u>
  - Good processing is favored by low molecular weight

Figure 43 Illustrating the dilemma in polymers

All polymers can be divided into two types that differ in their thermal characteristics as a result of one type being crosslinked and the other not. The polymers that are not crosslinked are called thermoplastics (meaning that they are still moldable after heating). The polymers that are crosslinked are called thermosets (meaning that they are not moldable after having been crosslinked).

Thermoplastics are not crosslinked and so they melt. Thermoplastics are solids that are heated and then molded as molten liquids or highly softened solids that are poured or injected or forced into molds. After entering the mold, thermoplastics are cooled to re-solidify. Because no chemical changes (reactions) have occurred during their molding, thermoplastics can be re-melted repeatedly. A good kitchen analogy for thermoplastics is candy.

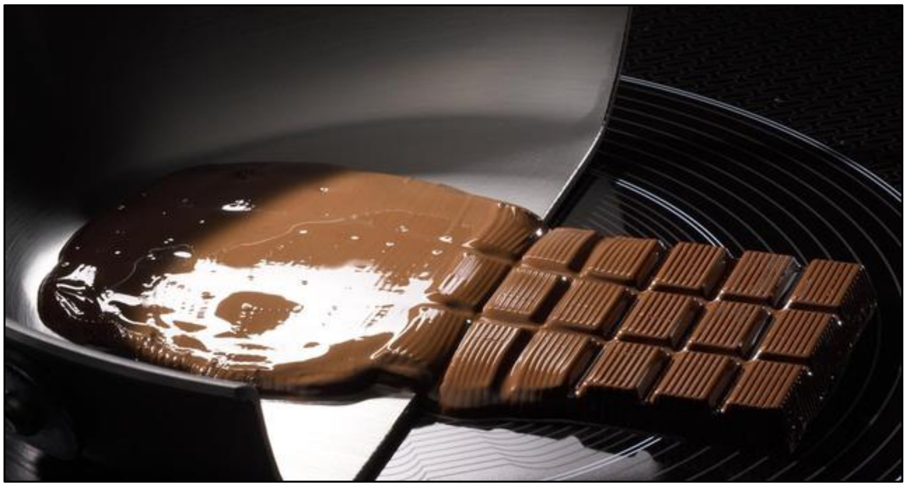


Figure 44 Candy as analogy for thermoplastics

Thermoplastics solve the properties/processing dilemma by compromise. They have molecular weights high enough to give generally good properties, but not so high that melting is too difficult. However, as thermal and mechanical properties become greater, the need for higher molecular weight or some other way to increase mechanical and thermal properties becomes a real problem if processing is to remain reasonably easy.

Thermosets are crosslinked so they do not melt. The process of crosslinking is sometimes called curing. Thermosets are usually loaded into the mold as liquids or low-melting solids and are then heated in the mold to solidify (harden) and during curing chemical reactions occur. A good kitchen analogy is baking a cake.

Figure 45 A cake as an analogy for thermosets

Solving the properties/processing dilemma with thermosets is logical and common. They are liquids to begin and then become high molecular weight solids after crosslinking. However, mistakes are very costly because the end product cannot be altered to correct most mistakes. Furthermore, curing of the thermoset to become a solid is usually a much longer process than simply cooling a thermoplastic to harden. Therefore, processing times for thermosets are often much longer than with thermoplastics.

Melting and decomposition of thermoplastics and thermosets can be easily illustrated by examining an electrical assembly that was exposed to a flame. This is shown in Figure 46 where the decomposed area from a thermoset (the circuit board and some components) is contrasted with the thermoplastics (wire insulation) that is merely melted and slightly misshaped.

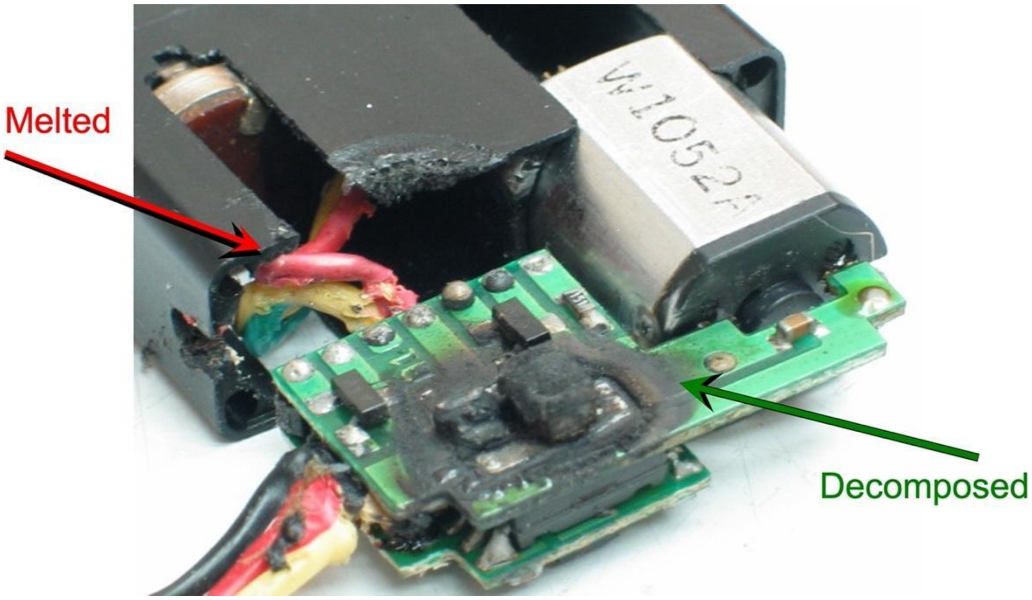


Figure 46 Electrical assembly demonstrating overheated thermosets and thermoplastics

By examining the viscosity of polymers as the temperatures increase, we can see graphically the differences between thermoplastics and thermosets. These plots are shown in Figure 47. Viscosities are a measure of how easily a liquid flows. High viscosity means the liquid flows slowly and is usually thick, like molasses. Low viscosity liquids flow easily and are usually thin like water. In general, as a liquid is heated, its viscosity drops, that is, it flows more easily.

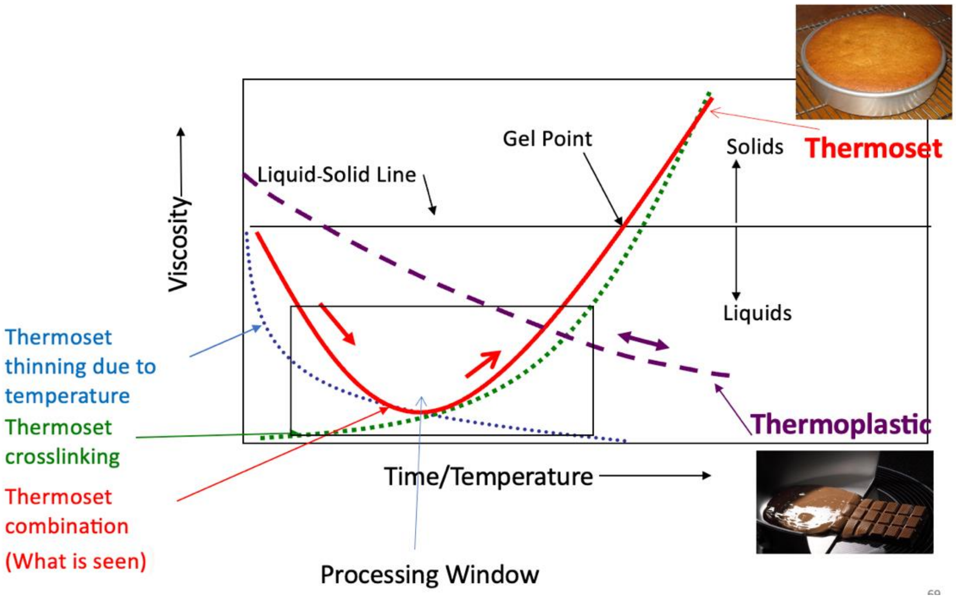


Figure 47 Viscosity versus temperature curves for thermoplastics and thermosets

Looking first at the thermoplastic curve (purple) we see that the line begins above the liquid-solid line indicating that the material begins as a solid. As the temperature increases, the viscosity of the material drops. It continues to drop as long as the temperature increases. The double-headed arrow means that the process of heating and cooling can be repeated and the same curve will be followed.

The thermoset story is more complex. Initially, before crosslinking, the viscosity curve (blue) drops with temperature. However, when crosslinking occurs, the viscosity of the material (green) shows a rapid increase in viscosity with temperature. What is observed (red line) is the combination of the blue and green lines. It shows an initial drop in viscosity and then a rapid increase in viscosity when crosslinking begins to occur. The bottom of the red curve has a box surrounding it that represents the temperatures at which processing (molding) should occur.

Another chart reflecting the thermal properties of thermoplastics and thermosets is shown in Figure 48. In this chart the typical thermoplastic is shown on the top of the linear graph in which some transitions are indicated as temperature increases.

- The heat deflection temperature is the temperature at which a plastic, when heated and simultaneously pressed, deflects by a certain amount.
- The glass transition is the temperature, determined from a flexibility measurement, when long-range movement of the molecules occurs. The texture of the polymer changes from hard and rigid to a softer, more flexible solid (somewhat like leather).
- The melting temperature is when the molecules are disentangled and can move freely. The polymer becomes a liquid.
- The decomposition temperature is when the bonds along the chain rupture and the polymer begins to degrade and turn into a char.

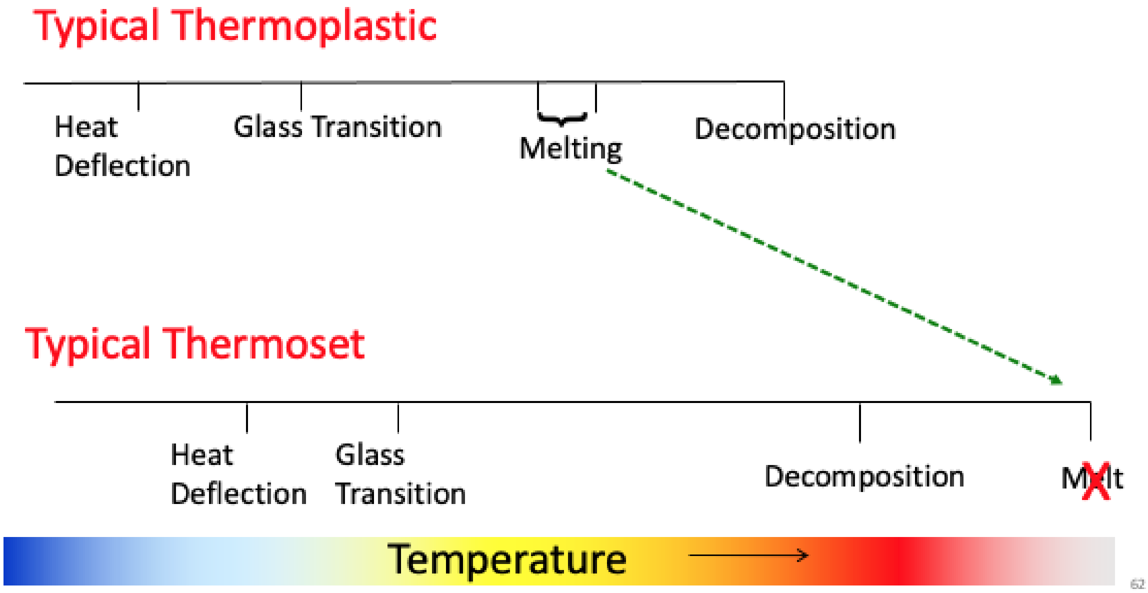


Figure 48 Thermal properties of thermoplastics and thermosets

The chart for a typical thermoset is very similar to the thermoplastic but some important changes are seen.

- The heat deflection temperature and the glass transition temperatures are somewhat higher for thermosets than thermoplastics because the molecular weights of crosslinked materials are higher and the molecules are held more tightly than in thermoplastics.
- The big change is the melting point. As shown, the thermoset melting point is moved above the decomposition temperature. Therefore, thermosets degrade before they melt.

Molecular Shape Principle

Many physical properties of polymers depend upon the shape of the polymer chain. For example, if the chain is relatively simple with few or small groups attached to the backbone chain, the molecule is flexible, somewhat like a snake. If the polymer is highly crosslinked and branched, like a tree, it is often quite stiff and brittle. If the polymer chain is stiff and straight, it is like a board and that often leads to good strength.

A very important molecular group in chemistry is the aromatic group that is shown in Figure 49. This six-membered carbon ring with hydrogens attached to five of the carbons is called the aromatic group. (It is named aromatic because some of the molecules that contain this group have a strong odor.) Each of the representations in the figure is equivalent. When the attachment group X (see the figure) is a hydrogen, the molecule is called benzene.

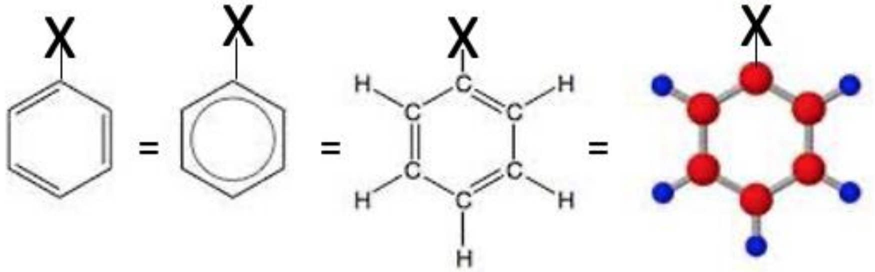


Figure 49 The aromatic group with X indicating where it is attached to another atom or group

The aromatic groups can be attached to many different atoms and/or groups, including polymers chains. Some typical attachments to polymers are shown in the Figures 50 and 51. In polystyrene the aromatic groups are attached to the carbons that form the backbone of the polymer. In Kevlar™ the aromatic groups are part of the polymer backbone. In the phenolic polymer the aromatic groups are the primary part of the highly branched molecule. As the number of aromatic groups on the polymer increases, the polymer is said to have greater aromaticity or greater aromatic character.

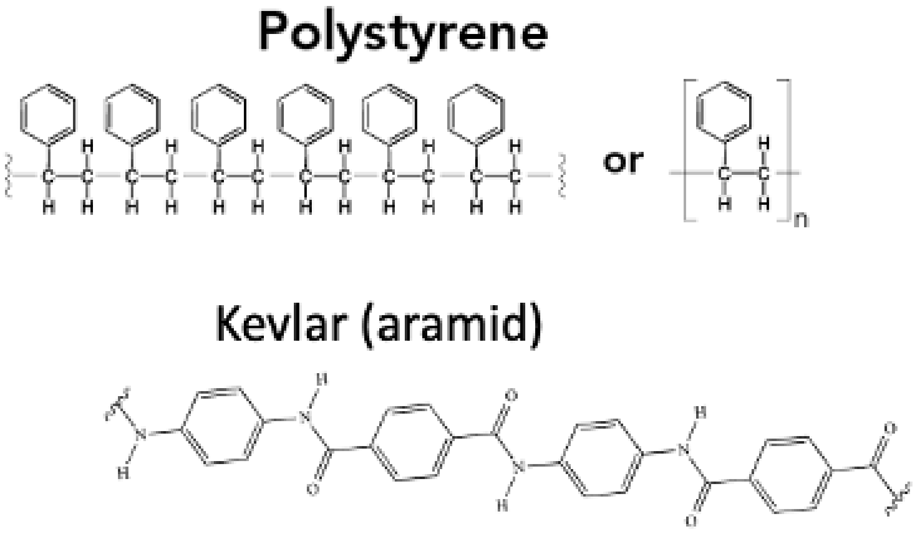


Figure 50 Aromatic groups on polymers

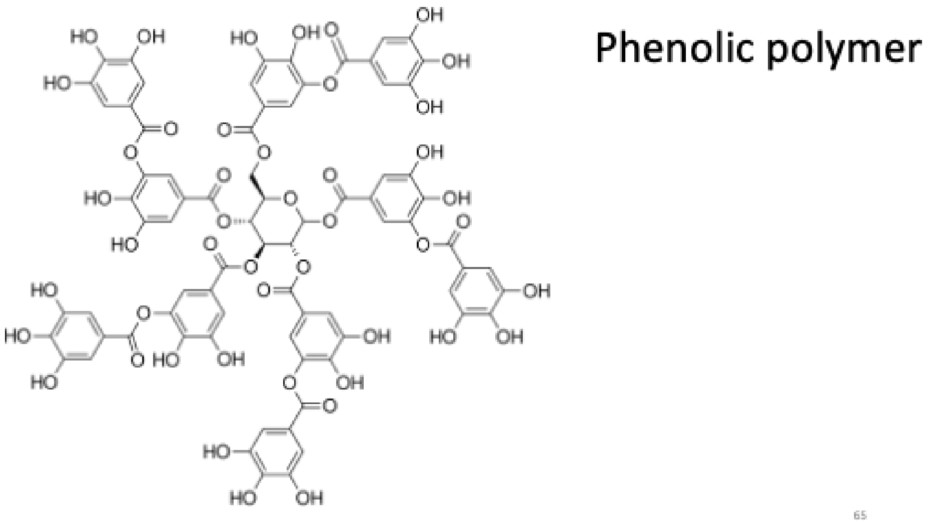


Figure 51 Aromatic groups making up most of the polymer

The aromatic group is very stable chemically and resistant to most chemical processes that a polymer might encounter. It is also resistant to most environmental forces. Because it is a large group and is quite stiff (maintaining an essentially flat shape), the aromatic group interferes with other atoms and resists being pulled or pushed by outside forces. When included along the backbone, the aromatic group makes the polymer stiff. Hence, aromaticity increases mechanical properties, and, because it resists motion, aromaticity also increases thermal stability.

If a molecule contains the aromatic group, it is said to be aromatic and it might be slightly aromatic, highly aromatic, or some descriptor in between. If there is no aromatic group, the molecule is called aliphatic. The effects of having an aromatic group or of being aromatic are given by the aromatic principle that is summarized in Figure 52.

Aromatic

Contains Aromatic Group

Aromaticity Increases Thermal Resistance

Aromaticity Increases Mechanical Properties

Aromaticity Increases Fire Resistance

Aliphatic

Does Not Contain the Benzene Group

It Often Has CH_2 Groups Instead

Aliphatic Content Increases Flexibility & Toughness

Aliphatic Improves Weatherability

Figure 52 Aromatic principle outlined

Fire resistance principle

Increasing fire resistance can be accomplished in many ways including cooling the burning area below the flammability point, removing the oxygen from the flame area, and chemically resisting the tendency of the molecules to react with oxygen.

As already discussed, adding aromatic character will increase flame retardance of a polymer because the aromatic molecules are stable and resist chemical reactions. Another common method to improve flame resistance is to add a filler (usually ground up rock) and these also resist reacting with oxygen. Some fillers also have absorbed water in its structure and these fillers release water when heated and that water helps extinguish the fire. The most common of these is alumina trihydrate ($Al_2O_3 \cdot 3H_2O$).

Other fillers that can be added to reduce flammability by smothering the flame (excluding the oxygen). These include substances that contain halogen (F, Cl, Br, and I), but these atoms result in smoke that contains the halogens and they can be irritating and might be toxic in large concentrations. Halogen atoms can also be reacted with the polymer so that they are attached to the chain. However, the smoke from these materials will still contain the halogen atoms and could be dangerous. Nevertheless, for some applications, the use of halogens is widely accepted to reduce flammability.

Crystallinity Principle

When some polymers solidify, the molecules pack together and form regions of high density. These areas are called crystalline regions and the polymer is called crystalline or, more accurately, semi-crystalline. In general, even in highly crystalline polymers, some of the molecules do not pack tightly but form areas where the polymers are disordered. These more random areas are called amorphous regions. These are illustrated in Figure 53.

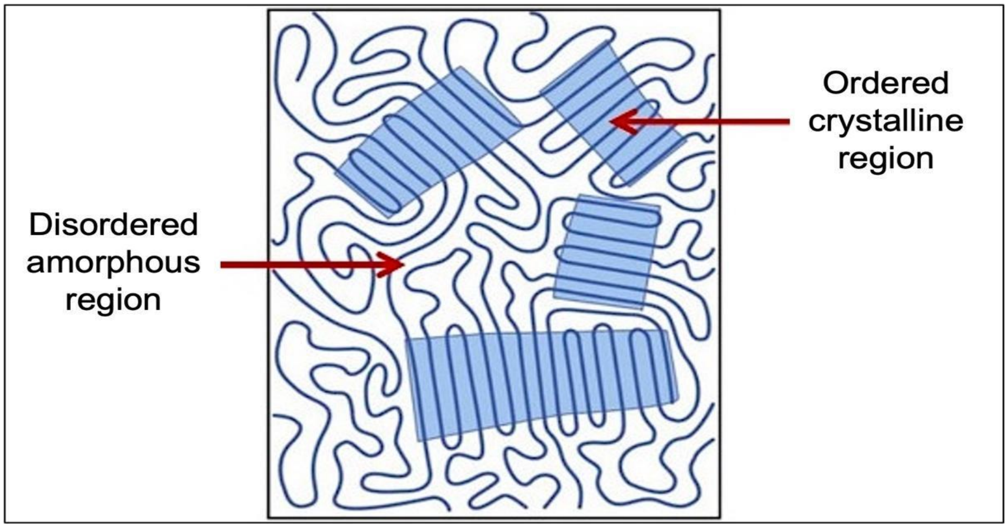


Figure 53 Crystallinity of molecules

The resin principle is that the crystalline regions are more stable than the amorphous regions and, therefore, require more energy to slide apart when subjected to pulling, pressing, or bending forces. Hence, mechanical properties are raised when the polymer is crystalline. In a similar manner, more energy is required to melt the crystalline regions and so crystalline polymers have higher melting points than amorphous polymers. When both amorphous and crystalline regions are present, the temperature range where melting occurs is usually broadened.

Crystallinity also reduces permeability, that is, the ability of a gas or liquid to pass through the polymer. The crystalline regions simply block the movement of the gas or liquid molecules. This can be an important property in applications such as hydrogen gas tanks and natural gas tanks for use in “green” cars.

Several molecular shapes affect the formation of crystalline regions. The most important feature that prevents crystallinity is when groups are attached to the polymer backbone, especially when the attached group is quite large. These large groups take up a lot of space and physically interfere with the packing of the molecules. Attached aromatic groups are a good example of a large group that prevents crystallinity.

Common Composite Resins

Almost any resin can be used as a matrix for composites as long as it meets the criteria for performance (being moldable, protecting the fibers, and transferring externally applied loads or forces onto the fibers) that are required of all matrix materials. The wide choice of resins for a matrix is especially true when the concentration of fibers is low (generally less than 30%).

However, this wide choice of resins at low fiber concentrations has a complication. As already discussed, the sizing (thin coating) on the fiber that ensures that the fiber bonds well to the matrix is an important factor for many of these resins, especially those that are not commonly used for composites. If the sizing is not chosen carefully, the fibers may not transfer the forces properly because the resin doesn’t bond well to the fiber. Consequently, if the resin is not commonly used for composites, it is best to purchase resins with fibers already incorporated into the pellets by the resin manufacturer or buy the fibers that have a sizing well known to work with the resin to be used as the matrix.

A few major families of resins are used when the reinforcement concentration is high (greater than 50%). These families are the most important resins for the majority of composite applications and each family is examined in this chapter. These resin types differ in curing methods, physical properties, and thermal properties. In addition, within each of these types, there are many variations that allow the resins to meet particular customer needs.

This chapter will describe the main characteristics of each family without attempting to explain the detailed chemistry of the polymers or of the crosslinking reactions that are most commonly used for that family. Rather, the explanation will be focused on the properties of the family and the general method of crosslinking from the standpoint of someone who is using the polymer to make composite parts.

Unsaturated Polyesters

This resin family, also called thermoset polyesters, is the most important for making composites with fiberglass as the reinforcement. This dominant position within the reinforced fiberglass marketplace is due to several factors, not the least of which is low cost. Unsaturated polyesters are commonly priced about 25% lower than vinyl esters and about 33% to 50% less than epoxies.

In addition to their cost advantage, unsaturated polyesters have advantages in ease of cure, ease of molding, a wide range of property possibilities, and an extensive experience base in developing technologies and design parameters. However, polyester thermosets have several drawbacks or disadvantages in properties and manufacturing such as relatively poor durability, brittleness, and air pollution difficulties during molding. In general, however, the advantages seem to outweigh the disadvantages and polyesters continue to be the resins of first choice for many fiberglass composite products.

Several companies make polyester resins and therefore have strong interests in their continued marketplace dominance. These companies are active in improving polyesters by creating new variations of the basic building blocks used to make unsaturated polyesters. It is just this possibility of widely varying properties that originally led to the adoption of unsaturated polyesters as the resin on which the fiberglass composites industry was built. Polyester thermosets have become so prevalent that references to broad categories of composites such as fiberglass reinforced plastics (FRP) and sheet molding compounds (SMC) automatically imply that the resin is a thermosetting polyester.

No list of reinforced polyester thermoset products can possibly be complete, but a short list can give some appreciation for the scope of its market. Essentially every brand of automobile and nearly every automobile model use polyester thermoset parts; some automobiles use polyester thermosets for essentially their entire body structure. Most small boats use polyester as the principal materials for the hull and often for the deck and, for sailing ships, many of the masts and other fittings. Other vehicles using polyester thermosets include golf carts, snowmobiles, and 4-wheelers. Most clothes washers, driers, and many other major appliances use polyester thermosets for pump housings, motor shrouds, and various other components. Tub and shower units, spas, building panels, and many other items of construction make polyester thermosets the major resin of the construction and home building market. Polyester thermosets are one of the major resin types for storage tanks and pipes used to contain non-corrosive chemicals in industries such as paper and pulp, oil and gas, chemical processing, and water transport and treatment. Virtually every major manufacturing industry in the world uses polyester thermosets in some part of their total operations. It can be safely said that polyester thermosets are practically everywhere.

Note that no mention has been made of polyesters used for soda bottles or for textile fibers. Although these materials are made from “polyesters,” the type of polyester used for these applications is different from those used in typical composites. The differences are that for composites the polyester is thermosetting and contains an active site (place where the polymer can be crosslinked) whereas for soda bottles and fabrics the polyester is a thermoplastic and does not have sites where crosslinking occurs. Because this book focuses on composites, the term polyester will mean the unsaturated, thermosetting type unless specifically referred to as a thermoplastic polyester.

Unsaturated polyesters are usually sold as a liquid mixture of the polyester polymer and the co-reactant (also called a hardener or reactive diluent) that is usually styrene. Unlike some thermosets, like epoxies, the polyester mixture is stable and does not begin to crosslink until another chemical, an initiator, is added. The initiator addition is done at the time of molding. The most common initiators are peroxides.

Although there are many factors (humidity, temperature, weather, resin uniformity, and variations in the structure details of the polyester) that have minor effects on the crosslinking reaction, the basic crosslinking mechanism is the same and is easily understood. During the crosslinking reaction, bonds are formed between the polymer and the styrene molecules and then between the styrene molecules and other styrene molecules until a bridge of linked styrene molecules joins two polyester polymers together. The number of styrene molecules in a typical bridge is about eight. The styrene bridges are the crosslinks between the polyester polymers. Because a polyester polymer has many active reaction sites, each molecule can form crosslinks with many other polymers. This results in a highly crosslinked structure involving all the polyester molecules.

Molding compounds are another form in which unsaturated polyesters are sold. In this case, both the styrene and the initiator are added to the polyester resin. The presence of the initiator means that curing (crosslinking) can begin immediately. To prevent rapid crosslinking, only heat-activated initiators are used and the resulting mixture is kept relatively cool to prevent curing. The advantage of using molding compounds is that nothing needs to be added at the time of molding, thus simplifying the molding operation and, generally, shortening the overall processing time.

Molding compounds are very popular in the automotive industry. In many auto applications, the molding compound also contains a filler. Common molding compound compositions are 25% resin, 15% fiberglass, 55% filler, and the rest are initiator and other minor additives. The filler reduces the overall cost, gives an opacity (cloudiness so that you can’t see through it), a smooth surface to the final product, and helps shorten the molding cycle. Molding compounds are sold as a mixture without a definite shape (called bulk molding compound or BMC) or as a sheet product (called sheet molding compound SMC). The sheet product can have longer fibers than BMC and is therefore used for large body panels where the longer fibers give improved mechanical properties.

Epoxies

Epoxies are the second most widely used family of thermosetting resins for composite applications (after polyester thermosets) and are the dominant resin used with carbon fiber. Epoxies are also used with fiberglass where the superior thermal and/or mechanical properties of epoxies are needed in applications such as some circuit boards, tanks holding corrosive liquids, and applications in hot environments.

All epoxy resins have two or more epoxy groups attached to the polymer chain and these are the active sites where crosslinking occurs. The epoxy groups are easily activated by a variety of molecules (called hardeners) that have another type of active group on each end. The result is a bonding of the hardener to the epoxy chain on one end and then a second bonding of the other hardener end to another epoxy polymer. This will tie the two polymers together with the hardener as the bridge between them.

The advantages of epoxies over most other matrix resins are the choices available for the structures of the polymer (between the epoxy groups) and the hardener (between the active ends). The choices for these intermediate portions of the molecules can range from full aliphatic (no aromatic groups) to highly aromatic (aromatic groups as part of the polymer backbone) for both the polymer and the hardener. Moreover, the length of the polymer chain is also highly variable so that the viscosity of the polymer can be chosen by increasing or decreasing the chain length. This means that mixing of the polymer with the hardener or wetout of the fibers can be facilitated by low viscosity. However, longer chains give higher viscosities but often give improved thermal and mechanical properties.

The ability to tailor the structure of the epoxies has led to a wide variety of properties where epoxies are superior to many other matrix materials. Some of those properties include the following:

- Low shrinkage during cure helps improve part dimensional stability and comes from having hardeners that are long enough to not pull the epoxy molecules together when crosslinking occurs.
- Excellent adhesion comes from good reactions between the active epoxy groups and fiber surfaces.
- Strength/stiffness comes because of the superior ability of the epoxy to transfer loads to the fibers and high aromatic content in the epoxy and/or the hardener.
- Resistance to stretching when under a small force means that the composite will retain its shape even when subjected to a continuously applied force. This is called creep and the resistance of epoxies results from the good bonding of the epoxy to the fibers and the stiffness of the epoxy matrix.
- Toughness, or the ability to withstand impacts, comes from having long polymers and long hardeners that can transfer shocks along their backbones. Sometimes rubber particles are added to the mixture of resin and hardener and these also absorb the shock of an impact and protect the part.
- Thermal stability comes from the ability to have a high degree of crosslinking by increasing the number of active sites along the polymer and the ability to have highly aromatic chains.
- Electrical resistance comes from being able to choose the intermediate segment of the chains and tailor for this specific property through the choice of non-conducting atoms.
- Water absorption resistance comes because there are few sections in epoxies that will absorb water
- Solvent resistance comes from having few segments to which other molecules can attach.
- Flammability resistance comes from having high aromaticity.

Not all of these properties can be achieved simultaneously because the choices of segment types are sometimes mutually exclusive (cannot occur at the same time). However, the ability to choose the construction of the segment leads to a wide choice of epoxies in the family.

Because most hardeners react so easily with epoxy polymers to begin the crosslinking, mixing is often done at the time of molding. However, many companies prefer to have the mixing done by a separate company and to apply this polymer/hardener mixture to the fibers. This creates prepreg, that is, preimpregnated fibers. Because of the reactivity of the polymer/hardener, prepregs must be kept at low temperatures (usually below 0°F) until just before putting the material into the mold.

Vinyl Ester

This thermosetting polymer is an attempt to combine the ease of curing of a thermoset polyester with the properties of an epoxy. Vinyl esters are made by attaching the same active groups that are present in unsaturated polyesters (called vinyl groups) onto the ends of epoxy molecules. Curing is done with styrene and initiators just as with polyesters. There is little difference in the curing methods of vinyl esters and unsaturated polyester.

Many properties are improved over polyesters by the incorporation of the epoxy molecule between the active groups. Mechanical properties, thermal properties, and solvent resistance are usually the properties most important for vinyl esters. For that reason, one of the major applications for vinyl esters is as an outercoat for polyester applications, especially in water environments. Therefore, gel coats for boats are usually vinyl esters. Pipes that will carry heated liquids are also a major market for vinyl esters.

Although vinyl ester mechanical properties are improved over thermoset polyesters, the vinyl ester properties are not as good as epoxies. But the lower price of vinyl esters and the ease of processing give vinyl esters a significant marketplace presence.

Phenolics

Phenolic resins were the first thermoset materials synthesized (under the name Bakelite® in 1907). They are still one of the most important thermosets, largely because of their superior thermal and fire-resistant properties.

Because the raw materials used to form the polymer are quite dangerous, the polymer is usually sold as an intermediate product. To make this intermediate, the reaction of the raw materials is stopped before crosslinking has occurred when the polymer is a thermoplastic. When any reaction is stopped at an intermediate stage, the process is called B-staging. The name derives from the concept that the totally unreacted raw materials are theA-stage; the intermediate thermoplastic material is the B-stage; and the fully cured and crosslinked material is the C-stage. Composite molders buy the B-stage material, add fiber reinforcement, and then cure to the final stage.

The fully cured material is one of the most highly crosslinked materials known and, therefore, is quite brittle and has high shrinkage when cured. The polymers made from these materials are called phenolics. They are highly aromatic materials and that leads to good strength but, more importantly for most applications, good thermal properties. Phenolics have low flammability and, even though the smoke is quite dark, the smoke is formed very slowly and, as a result, phenolics are used widely as the material for interior panels in airplanes, trains, buses, and ships.

The high aromatic nature also leads to good electrical properties. For years phenolics have been used to make electrical switches, circuit breakers, and other electrical devices. The thermal resistance of phenolics has led to their being used for handles of cooking pots.

When phenolics do burn, they do not melt (they are thermosets) but, rather, form a solid char that resists further burning and provides excellent thermal insulation. These properties have led to the use of carbon fiber reinforced phenolics as both nose cones and exit nozzles for rockets. The exit nozzle is subjected to very high temperatures as the gases from the burning fuel exits the rocket and gives it thrust. That causes the phenolic nozzle to char. The action of the exhaust causes the reinforced char to erode slowly in a process called ablation. As the char erodes, a new layer of phenolic is exposed and it then chars. Little by little the nozzle is worn away, but the rate of this process is predictable and, therefore, the thickness of the walls of the nozzle are made to guarantee that they are not fully eroded during the time of the fuel burn (with a safety margin). A similar process is encountered by the nose cone as it reenters the atmosphere. These are illustrated in the following figure.

The thermal insulating properties are especially noteworthy as shown in Figure 54. The outer skin of the nozzle is elevated no more than 10°F even though the gases are at 4000°F and the eroding nozzle material is at 500°F.

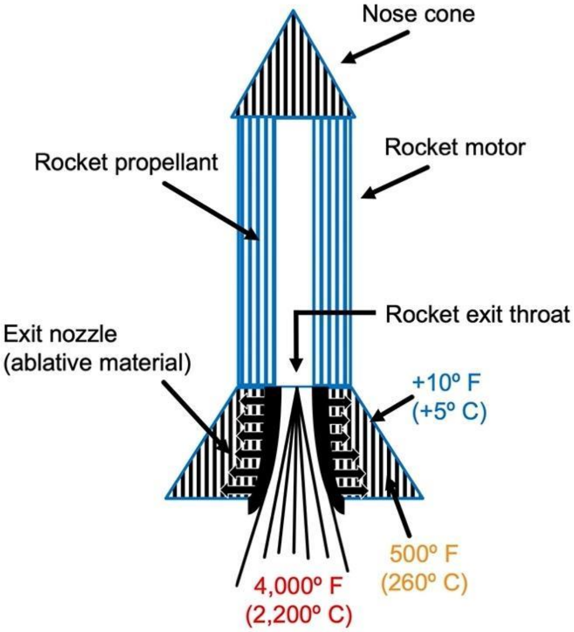


Figure 54 Phenolic composite in rocket nose cone and nozzle

One further application of phenolics is making carbon-carbon composites. These are materials in which a fully cured phenolic reinforced with carbon fiber is a precursor to the finished product. After being fully crosslinked, the product is further heated, usually in the absence of air. This turns the phenolic matrix into a char but has no effect on the highly thermally stable carbon fibers. When the matrix chars, gases are released and micropores develop in the matrix. These are detrimental to the thermal stability of the material at the temperatures under which the carbon-carbon will be used. (Probably more than 3000°F.) The part is then infused, under pressure and temperature, with additional matrix material, now formed as a gas. This fills the pores and the part is again charred. This process of infusing and charring may be repeated several times until the density of the material indicates that the pores are essentially eliminated. The process can take weeks to months to complete. The resulting material has the highest thermal tolerance of any carbon-based material.

In addition to their use in rockets, carbon-carbon composites are also used in aircraft brakes and in areas of aircraft that fly at hypersonic speeds, above Mach 5 (5 times the speed of sound).

Polyimides

As airplanes fly faster, certain areas of their skins get hotter. The resins that have traditionally been used for aircraft, chiefly epoxies, do not have the thermal stability to ensure that the stiffness and strength required for proper performance at the high temperatures is maintained. Carbon-carbon composites are too expensive for these applications. Therefore, a new family of resins was developed, initially by NASA, that meets these high temperature requirements. In keeping with the composite principles discussed in this chapter, NASA believed that the new resin family would be a highly aromatic thermoset. The NASA chemists were successful in developing a group of polymers that was based on the imide group, an aromatic ring with two 5-member rings attached to it. This molecular group was shown to have the thermal stability, strength, and stiffness necessary for advanced fighter aircraft. However, as might be expected from the principles discussed previously, the resins were very hard to process because they did not melt easily. Nevertheless, some parts were made using the new resin and they were successfully flown.

The processing difficulties of the polyimide proved to be an impediment to widespread adoption for new aircraft, like the F-35, that needed a high temperature resin for some body areas like behind the exhaust ducts. Fortunately, another new resin was developed that combined the structural and thermal advantages of imides with the curing simplicity of unsaturated polyesters. This new material was called bis-maleimide or BMI for short. BMI has better thermal properties than epoxies and is easier to cure than the earlier, NASA-developed polyimide. BMI has proven itself in both performance and manufacturing. The strength and stiffness at elevated temperatures, especially under wet conditions, have proven to be superior and that has led to its acceptance as the material for both naval aircraft and air force uses.

BMI has a high crosslink density and that has a negative consequence. The resin is quite brittle. Much effort has been given to toughening BMI and several routes are available. The results have been successful and these improved versions are currently in use although some additional steps in manufacturing the products are usually required.

Cyanate Esters

Cyanate esters are another group of thermoset polymers that have thermal and strength properties superior to epoxies. While not as good as BMI resins, several laboratories are working to improve the properties of cyanate esters, in part because of their superior ability to allow electrical signals to pass through them without reducing the electrical power. Furthermore, cyanate esters have their low moisture absorption. The major uses for this resin are radomes, antennae, stealth properties, and space structures.

Many electrical applications require low dielectric loss properties so that the signals are not absorbed by the resin, which causes weaker transmissions, return signals, and overheating of the components within the electronic enclosure. The cyanate esters have the lowest dielectric loss properties among the common and high-performance thermoset resins.

Thermoplastics

As discussed previously in this chapter, all resins are either thermosets or thermoplastics with the principal difference being thermosets are crosslinked whereas thermoplastics are not. Consequently, thermosets cannot be remelted after molding but thermoplastics can be remelted. The crosslinking process dramatically increases the molecular weight of the thermosets with subsequent increases in thermal and most mechanical properties. Thermoplastics, on the other hand, have advantages of much shorter molding times and, therefore, much higher rates of production. Because they are not locked into a rigid crosslinked network, the thermoplastic molecules can move more freely and that gives them higher toughness (resistance to impacts). These differences have led to some important applications for thermoplastics in the composites marketplace that need to be explored.

When production rates are high, as they are in the automotive industry and the many markets where relatively small plastic parts are made, thermoplastics dominate. In these markets thermoplastic composites are typically used when the non-reinforced plastic is not strong or stiff enough and the manufacturer concludes that fibers should be added to improve physical properties. The fiber percentage in these applications is generally below 40% and the fiber is almost always fiberglass. Some common examples of the thermoplastics that are used in these many markets include nylon, PET, polycarbonate, polyethylene, polypropylene, ABS, and many others. These are the engineering thermoplastic composites.

The automotive industry uses thermoset molding compounds for many body panels and other parts as discussed earlier in this chapter. These are made of fiberglass reinforced polyester but also contain mineral (rock) fillers. As a result, the weight of the parts is not significantly less than thin-gauge steel panels. However, to meet the emission and mileage standards, the cars must get lighter and yet the production rates need to be very high. Those criteria have led to the investigation of reinforced thermoplastics for body panels and other parts. The difficulty with engineering thermoplastics in many of these applications as well as most military aircraft is that these resins do not have the thermal stability required. Therefore, a group of high-performance thermoplastics has been developed (and is still being developed) for markets that require higher thermal performance. The most important of these high-performance markets are aerospace and high-end sporting goods.

As might be expected from an understanding of the resin principles discussed previously, a route to higher thermal tolerance resins is by increasing the chain length of the molecules and/or increasing the aromatic content. Both methods have been tried but increasing the aromaticity of the molecules seems to be the preferred method. What is sought are polymers that are stable to at least 400°F with minimal decrease in mechanical properties. To achieve this, the melting point will generally be 600 to 800°F. But processing resins that melt in this range has proven to be difficult. Many of the machines used in traditional thermoplastic and thermoset manufacturing do not have the capability to reach these high temperatures. That means that new equipment and, frequently, new manufacturing methods need to be developed to allow processing high temperature thermoplastics. For these reasons, high performance uses of thermoplastics have been slow to develop.

Recently some changes in the high-performance market have accelerated the development of high temperature thermoplastics. The development of drones, both small and large, as well as the concurrent development of small aircraft for individual air service has meant that production rates are expected to be very high for these aircraft and the use of high-performance thermoplastics seems appropriate. In conjunction with this private airplane development, the air force is developing attritable aircraft, that is, aircraft that are likely to be unmanned that will be inexpensive (comparatively) and will be sent into enemy territory as a swarm. The idea is that some of the aircraft will be shot down, but not all of them and so the enemy target will surely be destroyed. Again, advanced thermoplastics are the likely material so that the production rates will be high and the costs low.

The names of most of these high temperature thermoplastics are derived from their atomic group (monomer repeat unit) and relate to the principal atoms along their backbones. For those who are interested, these can be investigated further on the Internet. The abbreviations for the most common high-performance thermoplastics are PPS, PEEK, PEK, PEKK, PBI, PEI, and PSU. All of these materials have the aromatic group in the backbone and are, therefore, stiff, and high melting.

Because thermoplastics are solids at room temperature, some care must be taken with thermoplastic composites to ensure that the thermoplastic wets the surface of all the fibers. Not only must the fibers be coated with an appropriate sizing, but the thermoplastic must be properly infused so that the resin seeps into the fiber bundles and is still liquid (melted) during the fiber wetout process. Because this process is quite difficult, most composite part manufacturing companies that use thermoplastics as their resin purchase the resin and the fiber as prepreg.

The major groups of matrix materials can be compared in thermal stability. Figure 55 shows the regions in which the groups will retain their properties (as a percentage) versus the temperature at which they are tested (in both degrees F and C).

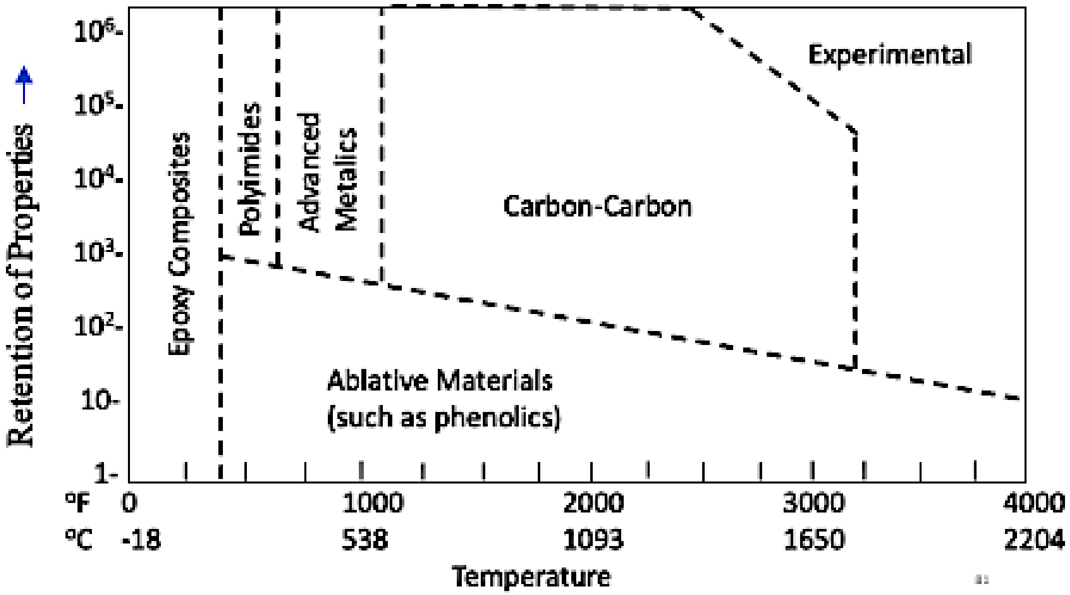


Figure 55 Retention of properties versus temperature

Fun Activity

Objective: Determine the relative toughness of thermoset and thermoplastic composites.

Procedure:

1. Obtain samples of flat panels (at least 8 inches x 8 inches) of the following materials: thermoset reinforced plastics (unsaturated polyester with fiberglass, vinyl ester with fiberglass, or epoxy with fiberglass) and thermoplastic reinforced plastics (nylon with fiberglass, PET with fiberglass, or ABS with fiberglass). All samples must have the same thickness and the same length of fiberglass.
2. Cut three samples for impact tests. These tests can be Izod, Charpy, or falling dart impact, depending on the type of testing apparatus available. If none of those are available, a steel ball that is dropped onto the samples will work.
3. Perform the test as described in the ASTM manual or, if not available, use the yardstick to measure the height and drop the steel ball onto each of the panels.
4. After testing, compare the toughness of the materials. In the case of dropping the steel ball, examine the panels for cracks on both sides and give a numerical rating (1 to 10) that reflects the extent of the cracks with 10 being no observed cracking and 1 being a shattering of the plate. Average the numerical value for the thermosets and then for the thermoplastics and compare. In the falling ball, the highest number would indicate the toughest material. In the Izod and Charpy tests, the highest number represents the poorest toughness as it is the height of the lever arm after impact and a high number means that little energy was required to break the samples. In the falling dart test, the apparatus measures the energy absorbed by the sample and, therefore, the highest number is the toughest.

Chapter 5 — Composites Design

The main objective in designing a composites part is to ensure that the part will be able to function properly during normal and extraordinary use conditions. Typically, the major considerations are the loads (forces) that will be placed on the part during use. These forces are determined from a knowledge of physics and the environment (conditions) in which the part will operate, and, generally, the use of computer programs that assist the designer. The types of forces that are most commonly encountered have been divided into five types that are shown in Figure 56.

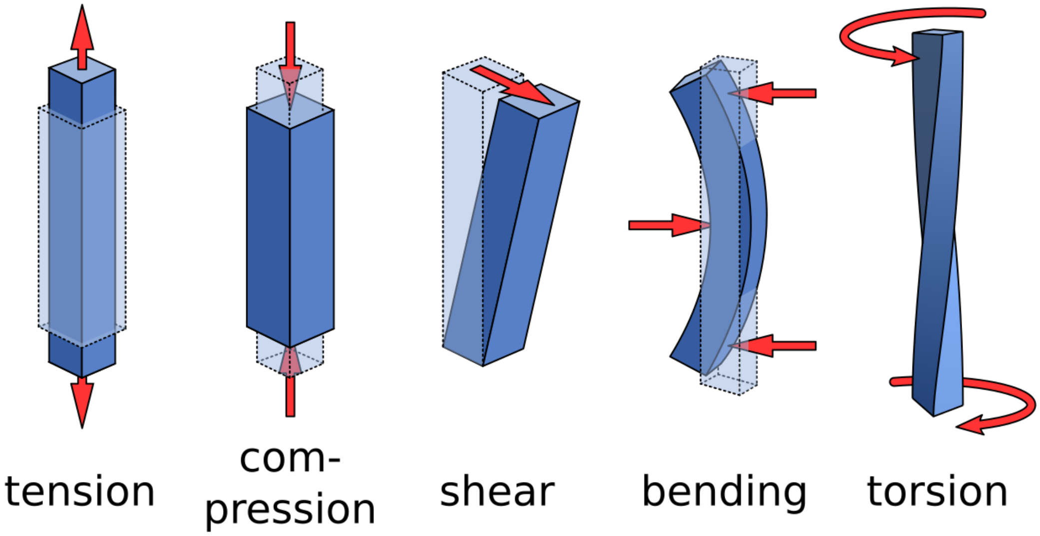


Figure 56 Types of forces (loads)

A few comments about each of these forces will be useful in understanding the methods used in designing a composite part.

- Tension or tensile forces are those that are applied by pulling on the ends of a part. It might be helpful to think of tension as the force that is applied to a rope in a tug-of-war.
- Compression is the opposite of tension. When compression forces are applied, the part is pushed together or pressed upon. Pillars supporting freeway bridges are under compression forces. A person standing on an artificial leg puts compression forces on the leg.
- Shear forces push against the side of a part when one edge of the part is anchored. Think of a stack of cards that are pushed and the cards slide across each other. The same force occurs when something is sliced or cut. Hence, the name of shears.
- Bending is also called flexing and occurs when one end or both ends are fixed and the force is applied to the middle. When this occurs, the side being pressed on goes into compression and the opposite side goes into tension. Therefore, bending is a combination of

compression and tension. A swimming pool diving board is under flexural forces when someone stands on the board.
- Torsion occurs when a part is twisted. It is similar to twisting a washrag to remove the water or the forces exerted on a cap as it is broken free from the lower portion and removed from a bottle.

Real life examples of the forces are shown in Figure 57.

Figure 57 Real life examples of forces

Force Analysis for Composites

After determining all the maximum forces that are expected to be present on a part during normal and extraordinary use, the composite part needs to be designed to withstand all those forces. This requires an understanding of how the forces affect the composite and how the composite withstands the forces imposed on it. Understanding the nature of composites when under a load is not easy because composites are inherently more complex than one-component systems like most metals, ceramics, and unreinforced plastics. The fiber reinforcements and the matrix have very different roles when loads are placed on the composites and this is different from most other structural materials. Still another complication is that composites are usually sold as thin sheets and, therefore, the composite structure is layered, whereas most other structural materials are a simple continuous mass.

Fibers Carry the Load

Simply put, the role of the fibers is to carry and withstand most of the structural loads (forces) that are placed on the composite part. The fibers will carry these loads (up to their ultimate strength) if they are oriented properly and do not break. Therefore, it is important to know the strength of the fibers when subjected to all of the types of forces listed above. This is done by testing in a laboratory. Fiber manufacturers list these values for their products and most composite manufacturers confirm the values for their particular part both through testing and through computer analysis.

The matrix merely transfers the loads to the fibers. This occurs because the loads press first upon the matrix because it is at the surface of the part. The matrix needs to be stiff enough to pass these loads on to the fibers and needs to be bonded to the fibers so that there is no slippage of the matrix against the sides of the fibers.

These functions of the fibers and the matrix are very strongly defined in advanced composites where the fibers are many times stiffer and stronger than the matrix. To understand the effectiveness of the fibers in fulfilling their role of carrying the load, engineers have been able to calculate the fraction of the total load that is carried by the fibers. This quantity is written as $\text{Load}_{\text{fibers}}/\text{Load}_{\text{composite.}}$ Two key factors are important in this determination. The first of these is how much stiffer are the fibers versus the matrix. This stiffness ratio is usually written as E_f/E_m, that is, the ratio of the stiffness or modulus of the fibers (E_f) over the stiffness or modulus of the matrix (E_m). The term “modulus” is just the engineering name for stiffness. The other factor is simply the volume of fibers as a fraction of the total volume of the composite and this is usually written in as V_f . The chart of these relationships is given in Figure 58.

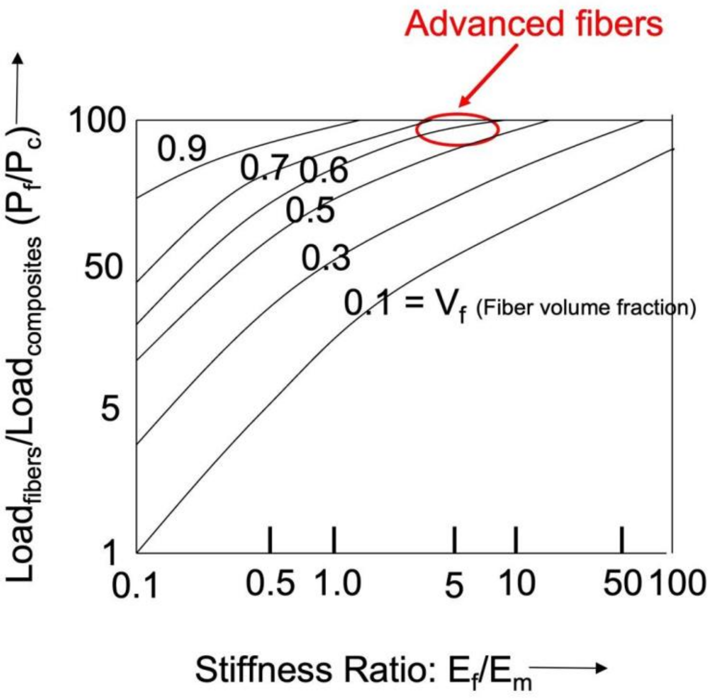


Figure 58 Amount of load carried by the fibers

The area that advanced fibers usually occupy is circled in the graph. Note that the stiffness ratio is usually 4 to 6 meaning that the fibers are usually 4 to 6 times stiffer than the matrix. The volume fraction is usually about 60%. When these conditions are met, the fibers carry about 90% of the total load placed on the composite.

The next important fact to remember about the load-carrying capability of composites is that the reinforcements only carry the load in the long fiber direction. This is illustrated by considering a rope. It is strong in the direction of the fibers but not strong in the cross direction, as shown in the accompanying figure.

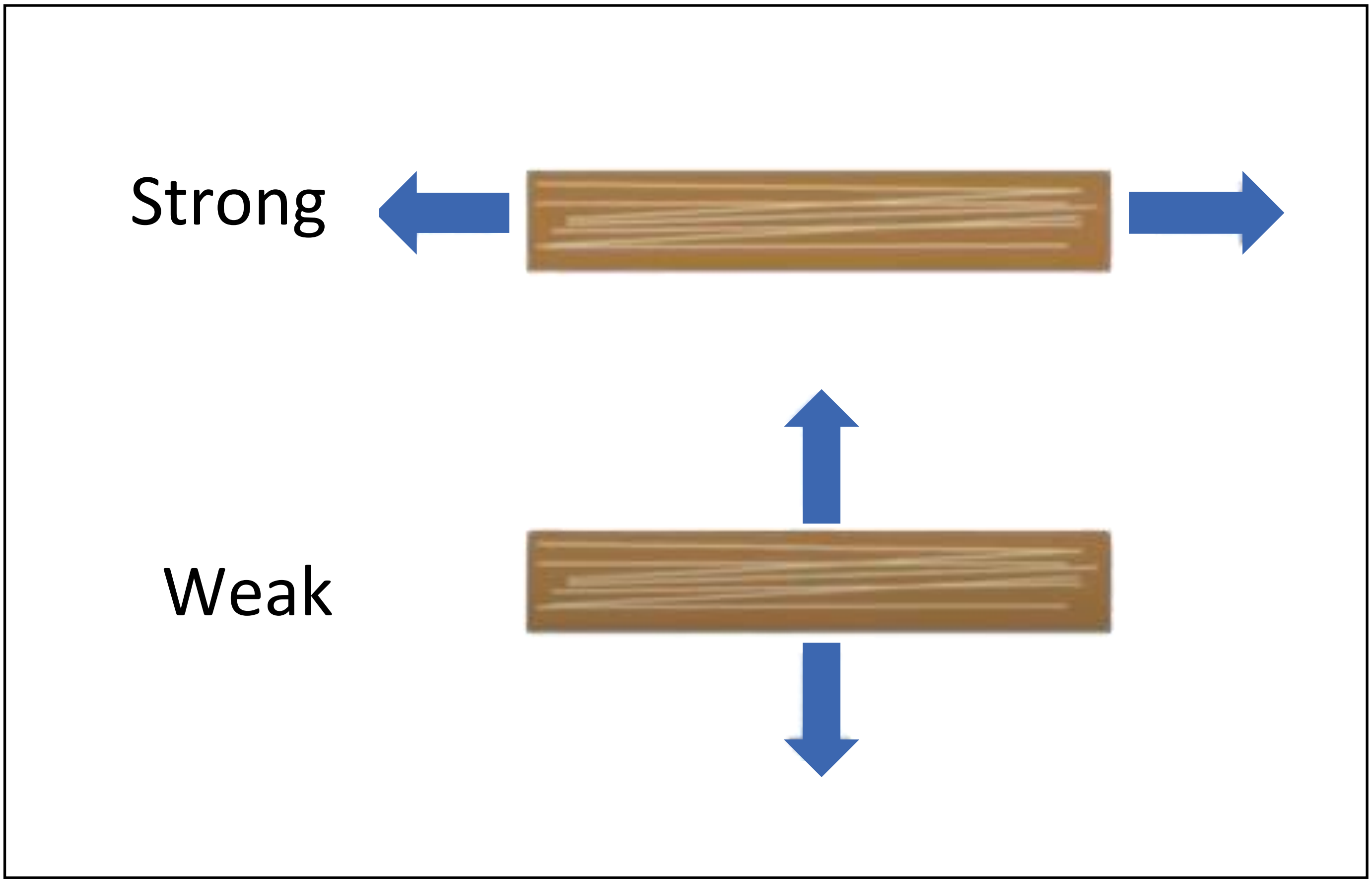


Figure 59 Fibers, like a rope, carry the load in the fiber direction

The decreased strength of the fibers as a function of the angle of the fibers with respect to the direction of the force or stress is shown in Figure 60. When the fibers are oriented in the direction of the applied force or stress, the strength of the composite is at its highest and then, as the fiber direction is changed away from the stress direction, the strength decreases.

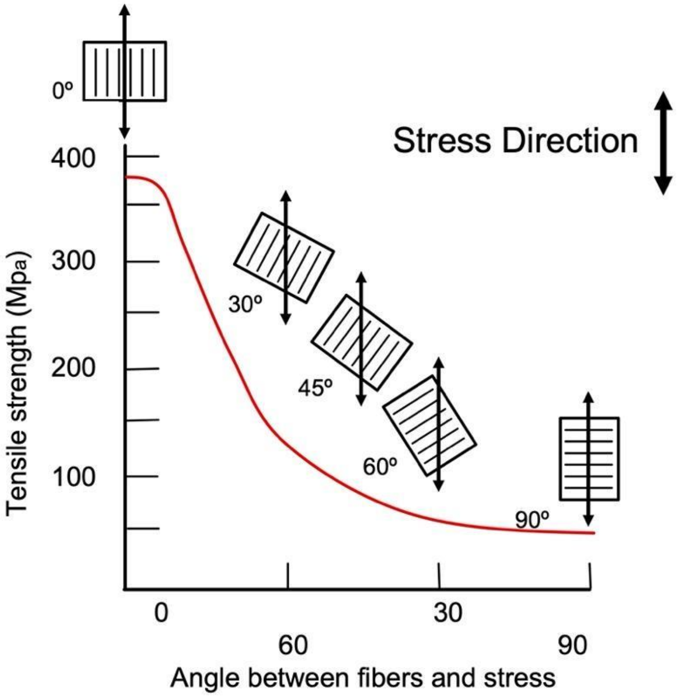


Figure 60 Strength as a function of fiber direction to the stress direction

Because fibers only carry the load in the fiber direction and yet loads may be imposed in multiple directions, fibers must be pointed in multiple directions. When the fibers are pointing randomly in all directions, the structure is called isotropic, meaning all directions are the same. (Bulk materials like most metals, ceramics, and non-reinforced plastics are generally isotropic.) When the fibers are oriented in a specific and uniform direction, the structure is called anisotropic. (See Figure 61.)

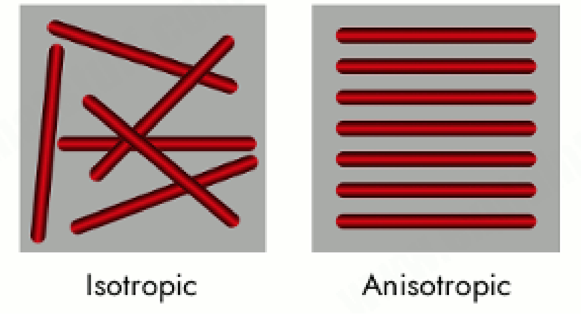


Figure 61 Isotropic and anisotropic fibers

Because composites are often sold as flat sheets (prepregs) with the fibers in one direction (unidirectional), an easy method of getting an isotropic structure is by making a layered structure with each layer having a different orientation. This arrangement is called pseudo-isotropic (meaning false isotropic). Such a stack of flat sheets is shown in Figure 62. Also in Figure 62 is a photo of the side of an actual layered composite showing that the layers are in different directions. (In some layers the sides of the fibers are seen and in other layers the ends of the fibers are seen.)

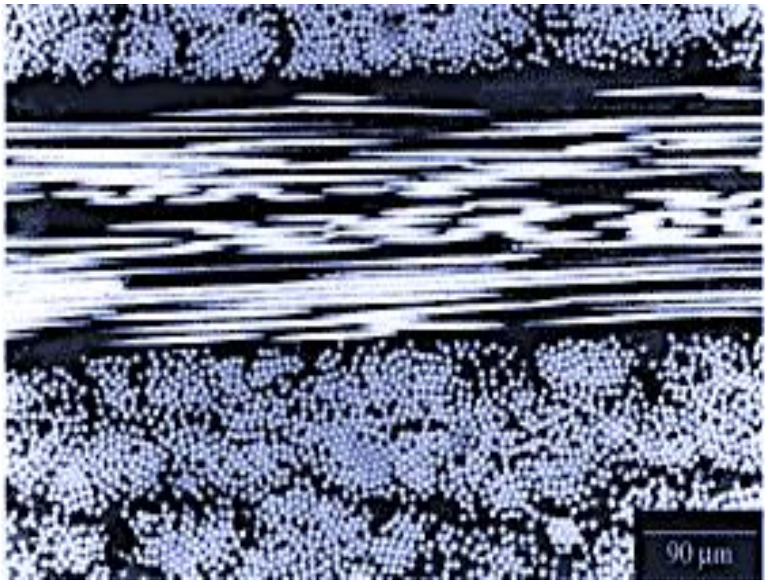


Figure 62 Pseudo-isotropic layering

Layering of Composites

To increase the strength of a composite part, the number of layers should be increased in the direction of the applied load. To allow composite designers to communicate with each other more easily, a layup direction convention (set of rules) has been established. This convention is illustrated in Figure 63. The X and Y directions are in the plane of the layers and the Z direction is vertical, perpendicular to the plane of the layers.

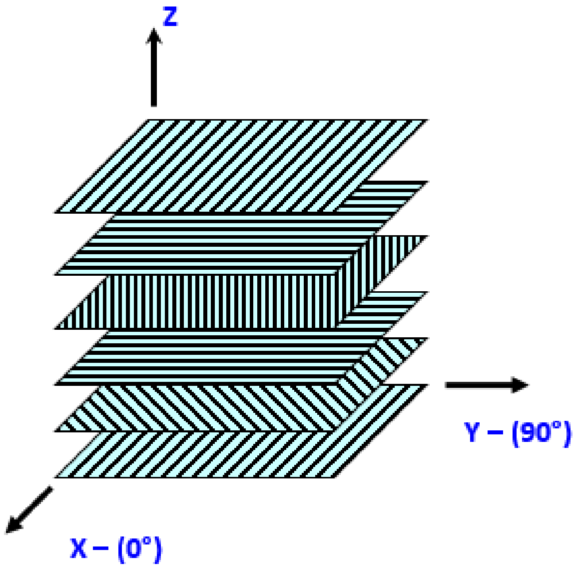


Figure 63 Direction convention for layups

As previously mentioned, part designers try to anticipate the loads that a composite part will encounter and design the layup (number of layers and directions of the fibers) to meet those loads. The most common angles for layup orientation are 0°, 90°, +45° (rotated to the left), and -45° (rotated to the right) although other angles can also be used. These are also the easiest angles to lay down when actually making the parts.

Experience has shown that not only the number of plies in a particular direction is important, but the order of the plies in the stack also makes a difference. This is illustrated in Figure 64.

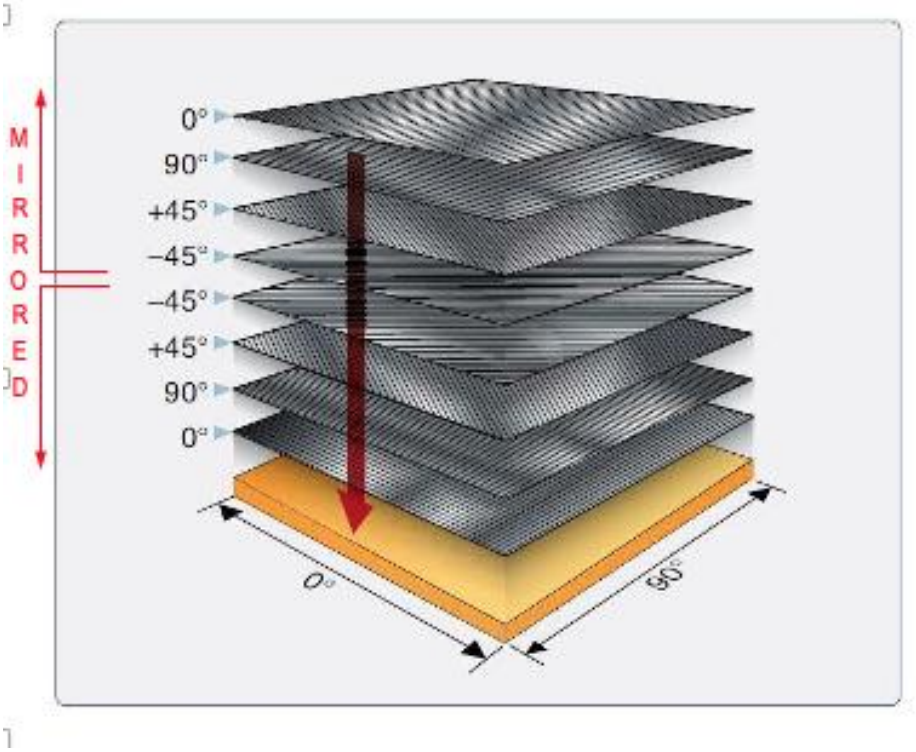


Figure 64 Layup sequence showing mirroring and balance

Notice that the sequence of plies moving up and down from the mid-point of the stack is the same. This feature is called mirroring. Also notice that the number of plies in the + (plus) direction is the same as the number in the – (minus) direction. This is called balancing. If both mirroring and balancing are not observed, the composite part will be warped after curing.

In addition to the use of unidirectional prepreg (as shown in Figure 64), layering can also be done with fabrics or fabric prepregs. When that is done, the warp of the fabric (machine direction of the fibers) is usually in the 0° direction and the weft will automatically be in the 90° direction. The fabric could also be oriented so that the fibers are in the +45° and -45° directions. Note that when this is done, some caution should be taken to ensure that balance and mirroring are maintained as some weaves have more fibers in the warp direction than in the weft direction, or vice versa.

Z-direction Considerations

The design discussion, thus far, has really only addressed loads encountered from the X and Y directions, that is, in the plane of the composite layers. Of course, loads could also come from the Z-direction, this is, in the direction vertical to the plane. The Z-direction might come from a load such as the weight of the occupant, aerodynamic lift or drag, gravity, or some imposed force. The effect of a Z-direction load is illustrated in the following diagram.

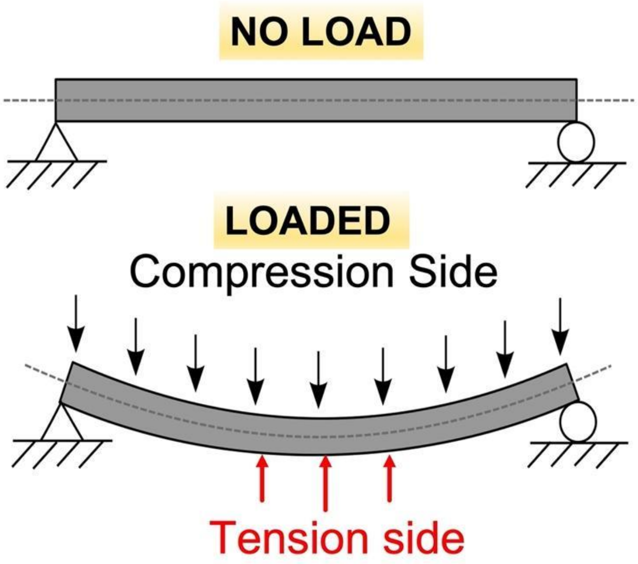


Figure 65 No load and Z-load illustrated

When a part is loaded in the Z-direction, the side facing the load is brought into compression and the opposite side is in tension. Note that at some point between the two side, a neutral plane is developed.

One strategy to increase the ability of the part to withstand a z-direction load is to simply apply additional layers of composite. This is shown below.

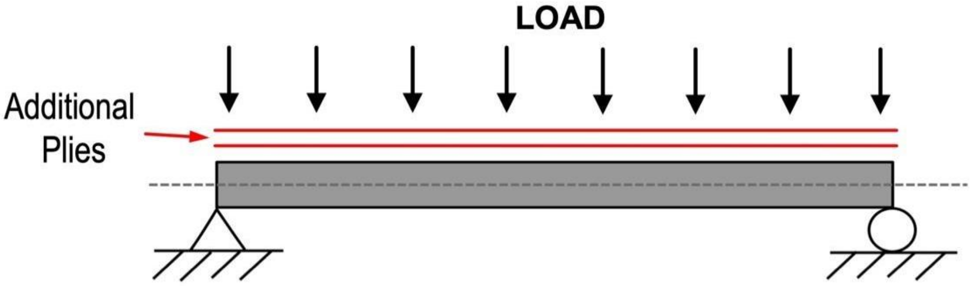


Figure 66 Adding plies to combat a z-direction load

Another method to combat Z-direction loads is to create a sandwich structure in which two layers of composite laminate (called face sheets) are separated by a solid core. This type of construction has been effectively used with metallic face sheets as well as composites. Normally, the face sheets are adhesively joined to the core material as shown in Figure 67.

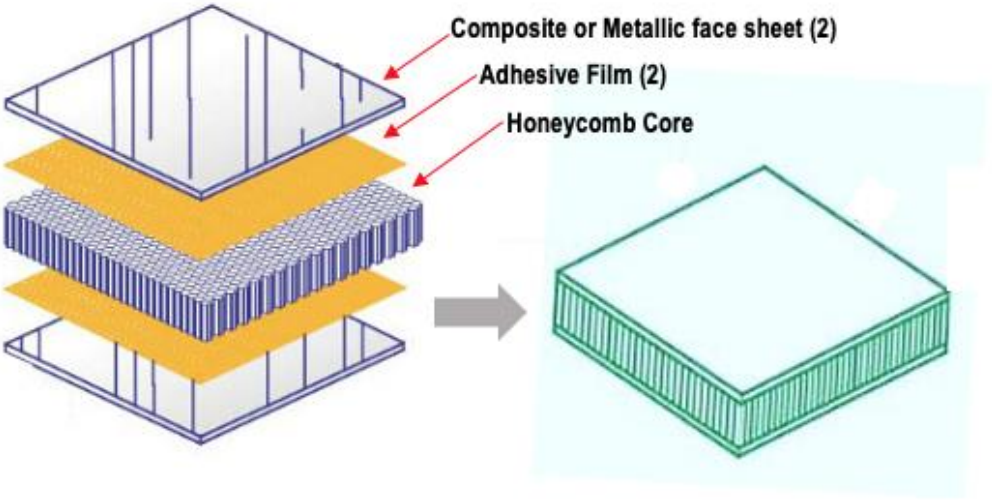


Figure 67 Sandwich structure construction

To maintain the lightweight requirements of advanced composites, the core materials are usually light weight aramid or aluminum honeycombs, rigid foams, or balsa wood end cuts. Photos of these materials are shown below. Fiberglass structures are also made using sandwich construction. The most common core material for fiberglass sandwich cores is wood, often plywood.

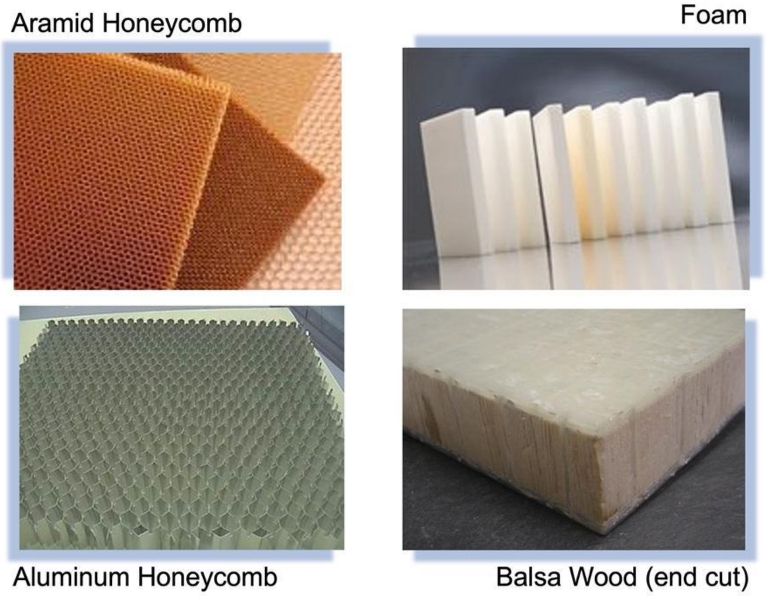
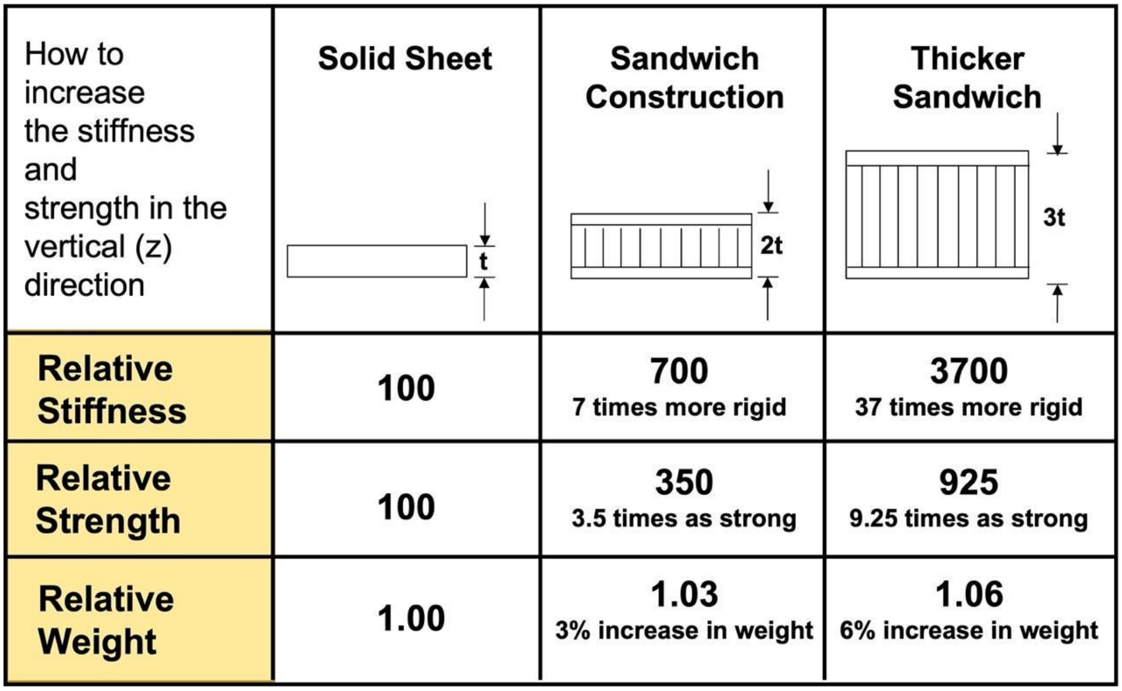


Figure 68 Core materials for sandwich construction

The effectiveness of using sandwich materials is astounding as can be seen in Figure 69 where the increases in Z-directional stiffness are shown for various core thicknesses.



How to increase the stiffness and strength in the vertical (z) direction	Solid Sheet	Sandwich Construction	Thicker Sandwich
Relative Stiffness	100	700 7 times more rigid	3700 37 times more rigid
Relative Strength	100	350 3.5 times as strong	925 9.25 times as strong
Relative Weight	1.00	1.03 3% increase in weight	1.06 6% increase in weight

Figure 69 Effect of core thickness on stiffness

While the sandwich construction makes large increases in stiffness, the increases in strength are much smaller, especially for the foams which can be crushed quite easily. Designers have, therefore, devised some other structures, based on geometrical principles, that increase both stiffness and strength in the Z-direction. Each of these design features has fibers that are in the general Z-direction, thus using the natural strength of the fibers to give stiffness and strength. Each structure is also supported in the X- and Y-plane in some way so that the fibers are continuous from the base to the end. The compound curves simply turn the fibers from horizontal to vertical whereas the others have a flat base that serves as a place for the adhesive to joint them to the main composite panel.

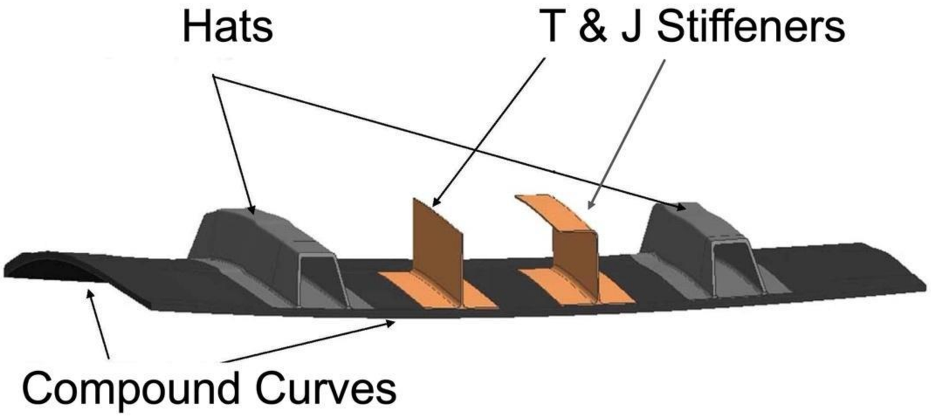


Figure 70 Geometrical stiffeners

Some photos of cores used in aircraft are shown in the figure below.

Figure 71 Photos of sandwich materials in airplanes

Failures

If the forces imposed on a composite are greater than the design predicted or the manufacturing methods did not make the composite as required by the design, failures can occur. Failures can also occur because of unexpected accidents. The most common causes of failure are impacts, over stress, over twisting, over bending, delamination, voids formed during layup or curing, and the presence of foreign object debris (FOD). Some of these are shown in the figure below.

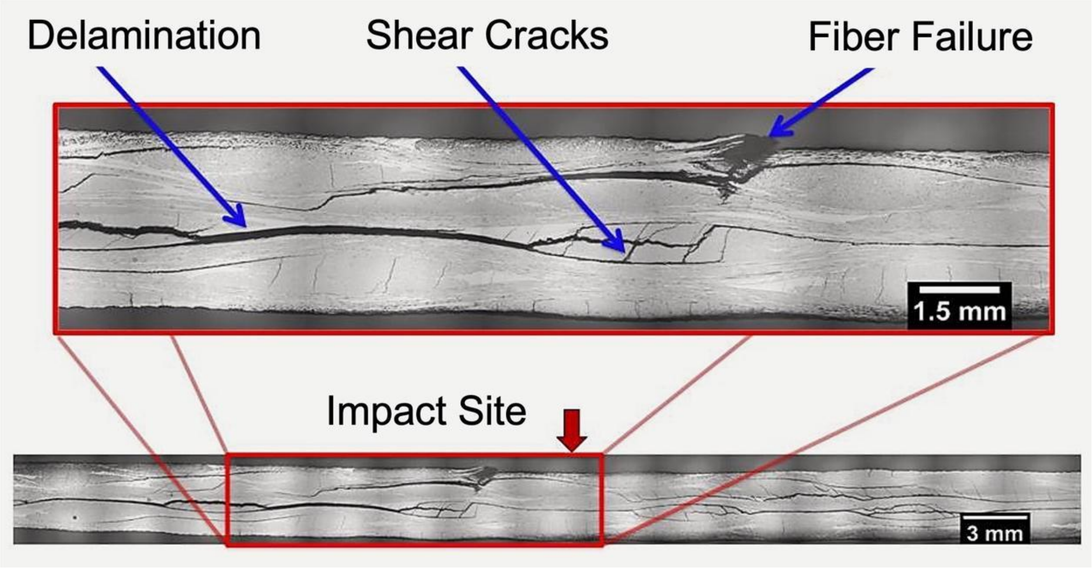


Figure 72 Failures in a composite laminate

The most serious failures are when the fibers break or when the fibers pull away from the matrix and no load can be transferred to the fiber. The loss of fiber integrity clearly means a reduction in the ability of the composite to carry a load. A corresponding consequence is that whatever load was applied to the composite will be borne by a reduced number of fibers and, perhaps, the load carrying capability of the fibers that remain will be exceeded. This will lead to catastrophic failure.

However, the cracking of the matrix material and/or the breaking of fibers, especially, will absorb energy. Because of the large number of fibers present in a composite, the amount of energy absorbed in considerable. As a result, composites are safer in crashes than most other materials because of this high energy absorption phenomena.

Comparison of Composites to Other Structural Materials

A graphical comparison of composites properties to aluminum and steel is given in Figure 73.

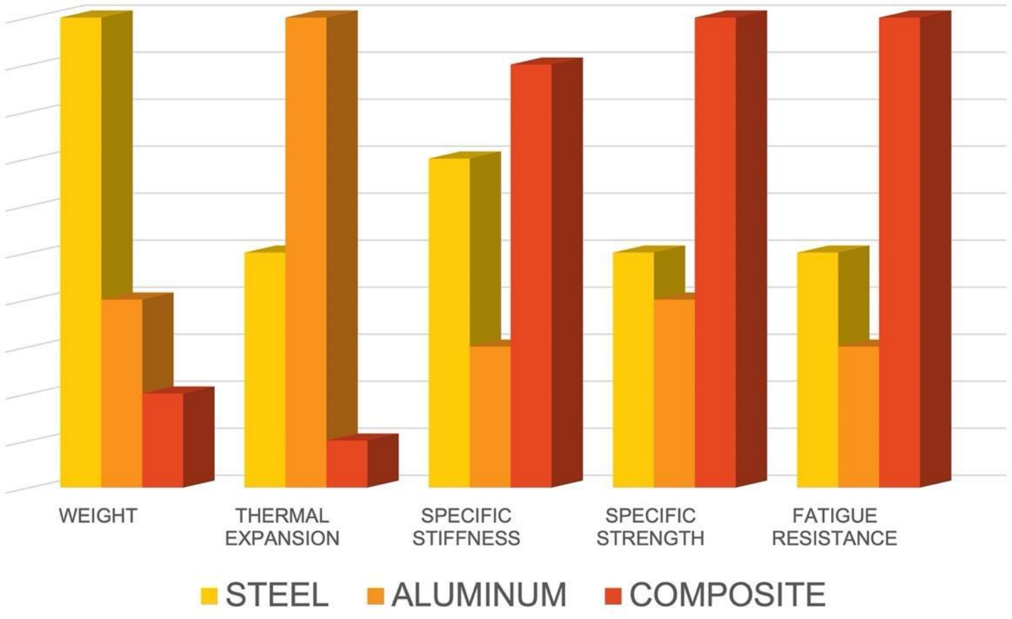


Figure 73 Property comparison of composites, steel, and aluminum

Clearly composites weigh less than steel (about a sixth as much) and aluminum (about a two-thirds of the weight). Because the fibers are so stiff, they hold the matrix in place over a wide range of temperatures and, therefore, the expansion of the composite when it gets hot (called the coefficient of thermal expansion, CTE) is much lower.

The specific stiffness and specific strength are significantly higher for composites than for steel or aluminum. The specific values mean that the weight is considered. Another way of saying this is, if the strength or stiffness is divided by the weight, the specific values are determined.

The fatigue resistance is better for composites indicating that over many use cycles, the composites retain their properties better. This is due to many factors including the ability of the fibers to be flexed many times without breaking and the presence of the fibers as “crack stoppers.” When a crack starts in a homogeneous material like steel or aluminum, it propagates easily through the material. However, when a crack starts to spread in a composite, the energy of the crack hits a fiber and is dissipated along the fiber’s surface, thus preventing the crack from continuing to grow.

Fiber Length Considerations

In general, increasing fiber length will increase the strength of the composite, in some cases as much as 25% higher when the fiber length is doubled. Stiffness is also increased with longer fibers but the effect is not as great as with strength. While not fully understood, the increase in strength is probably due to several factors. It is known that abrupt changes in the internal uniformity of a composite create points where energy is higher than the surrounding, more uniform areas. This higher energy at change points means that cracks are more easily initiated at these change points and when cracks form, the strength decreases. Hence, with short fibers, there are simply more fiber ends and, therefore, more abrupt changes in the internal uniformity of the composite.

The presence of foreign objects, like dust or even voids, also has the effect of decreasing strength in composites because these also cause abrupt changes in the internal uniformity. An interesting example that points this out was seen in a particular brand of golf club shafts. The company making these shafts reasoned that by putting a short (about 3 inches long) reinforcement of boron fiber in the shaft at the place where the head and the shaft join together, the club would have greater stiffness and, therefore, give longer drives. However, the company found that in use, the shafts would frequently break just at the upper end of the boron fiber—the location of abrupt discontinuity.

Another advantage of longer fibers is that there is more length onto which the matrix can transfer the loads. Experiments have shown that when the fibers are chopped to ever shorter lengths, they will become so short that the matrix can no longer transfer loads and the presence of the fiber as a reinforcement disappears. Hence, longer fibers have better load bearing capabilities.

The effect of abrupt changes is also important when decreasing the thickness of a composite by decreasing the number of layers. This thinning of the composite thickness is done routinely in airplane wings because thinning at the ends of the wings saves weight in the areas where the loads are not as high. In the Boeing 787 this thinning can be seen during flight when the tips of the wings curve upward due to the lift forces on the wing, coupled with thinner composites. The manufacturers have found that strengths are better when this thinning is done gradually using a tapering technique. For example, if the thickness is to be reduced from 6 layers to 3, the reduction is better when a layer is dropped every few inches rather than dropping all the layers at the same time.

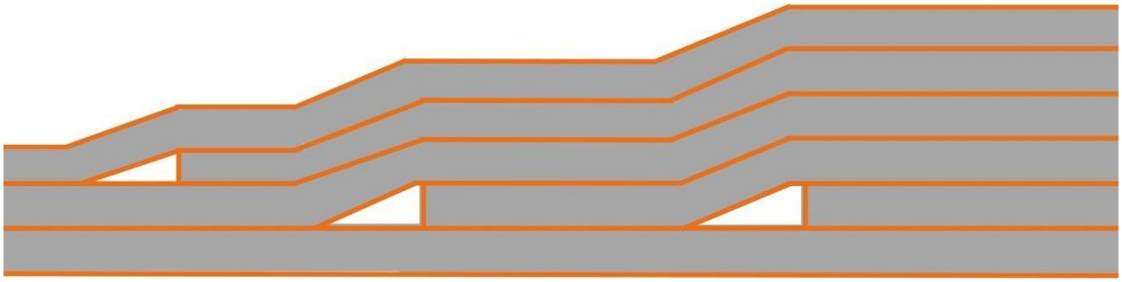


Figure 74 Tapering to reduce composite thickness

Fun Activity

Objective: Discover the crush strength of various core materials.

Procedure:

1. Obtain a variety of core materials. Some suggestions are rigid foams, aramid (Nomex□) honeycomb, aluminum honeycomb, balsa wood end cuts, and particle board.
2. Cut out three samples of each material into squares approximately 6 inches x 6 inches.
3. Weigh each sample and note the differences in weight.
4. Using a plate attachment on a tensile test machine, determine the compressive strength of each material. (If a tensile machine is not available, the compression differences can be determined by measuring the changes in height with weights pressing down on the samples.)
5. Average the compressive strengths from each sample.
6. Determine the ratio of the average compressive strength to the average weight for each material.

Chapter 6 — Composites Manufacturing

The most important tasks in manufacturing composites are to place the fibers properly according to the design and to ensure that the correct amount of resin completely coats all the fibers. These tasks need to be done with precision and good repeatability. Several machines have been developed to assist in performing these tasks, some almost without human intervention. Some other manufacturing processes remain largely manual. The choice of process and the degree of automation depend upon the resources of the company, the machines already available to make the parts within the company, and the nature of the product. Some products are so complex that manual methods are the best while other parts, especially large ones with simple curves, are more likely to be fully automated. The amount of fiber, length of fiber, and required precision of placement also affect the choice of manufacturing process.

In this chapter each of the commonly used manufacturing processes will be examined. The operation of the process will be explained, advantages and disadvantages of the process noted, and products commonly made using the process identified.

Traditional Thermoplastic Molding

At low concentrations, reinforced thermoplastics are usually molded using the methods that are traditional for unreinforced plastics, with only minor variations to allow for the reinforcements. These manufacturing methods are described in much greater detail in textbooks on plastics materials and processing such as Plastics: Materials and Processing by Brent Strong (available for free on the website ProfessorBrentStrong.com.) The traditional thermoplastics manufacturing methods include injection molding, extrusion, blow molding, rotational molding, thermoforming, casting, and others that are variations of these.

By far the most important of these methods for thermoplastic composite parts is injection molding. In this process small thermoplastic pellets (often already containing fibers if the part is to be reinforced) are fed into a hopper that is mounted over an opening in the machine. The pellets drop into the heated barrel portion of the machine in which a screw turns. The heat plus the action of the screw melts the plastic pellets and moves the molten material forward in the barrel where it is temporarily collected in a pool at the end of the barrel. At the forward end of the barrel is a tube that leads to a mold that contains cavities that give shape to the part. At the appropriate moment in the molding cycle, the screw slides forward and pushes the pool of plastic through the channel into the cavity where it is cooled. When the part is cold and rigid, the mold opens and the part is ejected.

Most of the time, when reinforced plastics are molded, the reinforcements are added to the plastic by the resin manufacturer/supplier. Few operating changes are required to mold these reinforced plastics except that the reinforcements might impede uniform movement of the plastic and the reinforcement through any small diameter areas in the process such as the tube connecting the machine with the mold cavity and the entry (gate) into the cavity. If that occurs, the tube diameter and/or the gate will need to be enlarged.

The reinforced plastics parts made by injection molding are generally small and, because the cycle times are short, quite inexpensive (except for the purchase of the mold). Therefore, many automotive parts, especially those under the hood, are made by injection molding. Applications where the part might be pressurized in use, like filter housings, are also commonly made by injection molding and often are reinforced.

Extrusion is similar to injection molding except that instead of pushing the plastic into the cavity of a mold, the screw turning forces the plastic through an orifice in a metal plate that is attached to the downstream end of the barrel. This metal plate and its housing are called a die. The plastic emerges from the orifice in the die as a shaped material that enters water baths to be cooled.

Extrusion is a continuous process used to make parts that are generally long and have a uniform and constant shape. Some examples of reinforced extruded products are rods that require fibers to improve stiffness, tubes that are pressurized, and channels that protect easily damaged corners.

Some of the other common thermoplastic molding methods like thermoforming and blow molding involve heating the plastic to the softened state (not fully melted) and then while in a softened state, forcing the plastic into a mold with either mechanical pressure or air pressure. This forcing causes the plastic to stretch to fill the inside of the mold. When the plastic is reinforced, the stretching can be a problem as the fibers may not move with the plastic. This could cause tears in the plastic part. Therefore, these processes are not frequently used for making reinforced plastic parts.

Another process that has some problems with fiber reinforcements is rotational molding. In this process a powdered plastic is rotated in a mold (usually quite large) while inside an oven. The plastic powder melts and sticks to the walls of the mold, thus building up the wall thickness. This is done until all the plastic placed in the mold is against the walls. When reinforced, the grinding of the plastic into a powder will, of course, reduce the length of the reinforcements and that will reduce the effectiveness of the reinforcements in strengthening and stiffening the part.

High performance thermoplastics melt at higher temperature than the traditional thermoplastics just described. If the injection molding machine and/or extruder is capable of the higher melt temperature, then the high-performance thermoplastics can also be molded using these methods.

Note: The remainder of the processes in this chapter will use thermoset resins unless specifically indicated otherwise.

Open Molding of Fiberglass Composites

The oldest and, probably, the simplest method of molding thermoset composites is still used extensively to make fiberglass parts. This process is called hand layup and is done simply by putting the fiberglass into an open mold, either concave (called a female mold) or convex (called a male mold). The fiberglass is usually a mat but could be woven fabric. After the fiberglass is positioned properly, the unsaturated polyester resin (with the initiator already added) is poured onto the fiberglass and rolled to mix the resin into the fiberglass. When the resin wets the fiberglass, there is a subtle change in sheen or color and that helps the operator know that the fiberglass is wetted. If more than one layer of fiberglass is needed, it is best to coat each layer after it is placed into the mold. Curing is then done either by heating the mold in an oven or by simply waiting for the curing reaction to occur. This choice depends upon the type of initiator chosen.

A diagram of the hand layup process and a photograph of an actual operation are shown in Figure 75. Note that in the diagram the mold is concave and in the photo the mold is convex, thus illustrating both types of molds.

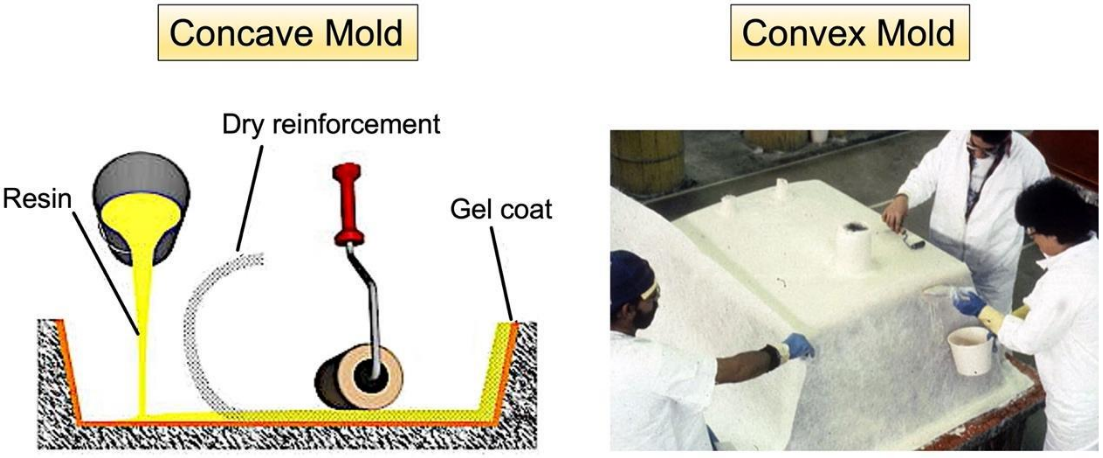


Figure 75 Hand layup method for fiberglass

A more automated method for making fiberglass composites in an open mold is called sprayup. In this method the fiberglass roving is fed into a spray gun that has a chopper attached. As the fiberglass moves into the spray nozzle area, the fibers are chopped (usually to about 3-inch lengths) and are entrained into a spray of the pre-initiated resin. The fibers are sprayed into or onto the mold to the thickness called for in the design. Rolling of the fiber to ensure wetout is often required. As with hand layup, the mold is then cured either by heating or by simply waiting for the curing reaction to occur.

A diagram of the process and an actual photo of the spraying are shown in Figure 76.

Figure 76 Sprayup method for making fiberglass composites

In both of the open mold processes one side of the part, the side against the mold, will be smooth and look finished (called the appearance side) while the opposite side will be rough. In many products, such as boats, tub and shower units, and wall panels, the appearance side must also have some protection against sunlight, rain, and other environmental factors. The appearance side is also often colored and opaque (cloudy) so that the fiberglass strands cannot be easily seen. To achieve this type of appearance side, a special resin, called a gel coat, is applied to the mold surface directly before any fiberglass is placed in the mold for concave molds and is applied afterward for convex parts. The gel coat resin will often have UV stabilizers, colorant, and other additives added before it is applied. Some manufacturers use a higher-grade unsaturated polyester resin or even a vinyl ester for the gel coat. The gel coat gives the part special protection against damage by the environment.

Before placing the fiberglass on top of the gel coat, it is common to partially cure the gel coat layer so that it is not pushed aside when the fiberglass is added. But it is best if the gel coat is still somewhat soft and not fully cured. (This partially cured state is called the gel state and that gives the gel coat its name.) When only partially cured, the gel coat will bond better to the layers of fiberglass that will be added afterwards. To assist in opacity, a very thin glass mat or fabric is placed behind the gel coat and before the heavier fiberglass layers are added. This thin layer, called a veil, blocks the view of any fibers below and prevents the fibers from moving into the gel coat layer.

Open Molding of Advanced Composites

Although some open molding of advanced composites is done by hand and at other times by automated machine, both methods are much more complex and precise when compared to fiberglass open molding. This higher process complexity, along with the much higher cost of materials, are reasons that the advanced composite costs many times as much as fiberglass parts. Each step in the molding of advanced composites is designed to ensure that the fibers are precisely placed and the optimum amount of resin is added and curing is done in the best way. Improvements are being made to the open molding of advanced composites process, but the general system originally developed in the 1970s is still largely in place.

Making and Cutting Prepreg

Rather than add resin themselves, molders making advanced composites almost universally use prepreg. This not only improves the likelihood of getting the right amount of resin and a very precise alignment of fibers, but it also eliminates a messy step in composite manufacturing where liquid resin is applied to the fibers. The molders generally agree that this step is best left to specialists who have the equipment and space to do it correctly.

Because each layer of prepreg in a multi-layer composite stack might have the fibers in different directions (such as 0°, +45°, -45°, 90°, etc.) and might be a different shape (some part of a taper, for example), the prepreg is often cut automatically on a cutting table with a head that is computer controlled. Such a cutting table is shown in the figure below. When the details of direction and shape of each layer are put into the computer controlling the cutting head, a cutting layout pattern can be created that will minimize the amount of prepreg needed and will then cut each of the layers. Operators can then pickup each layer and assemble the stack in the correct order as specified in the design. The stack can then be sent to the person who will layup each layer in the mold. Having the stack pre-assembled simplifies the layup process and reduces the chances for error. This cutting and stacking process is called kitting.

Figure 77 Automatic prepreg cutting machine

Prepreg Layup and Bagging

To further assist the person laying the prepreg in the mold, some molders have laser alignment devices that are mounted overhead and shine a laser light line onto the surface of the mold in the direction that each layer is to be placed.

After removing the backing sheet, each layer is placed into the mold and smoothed to ensure that it is adhering to the mold or to other layers that have been previously placed.

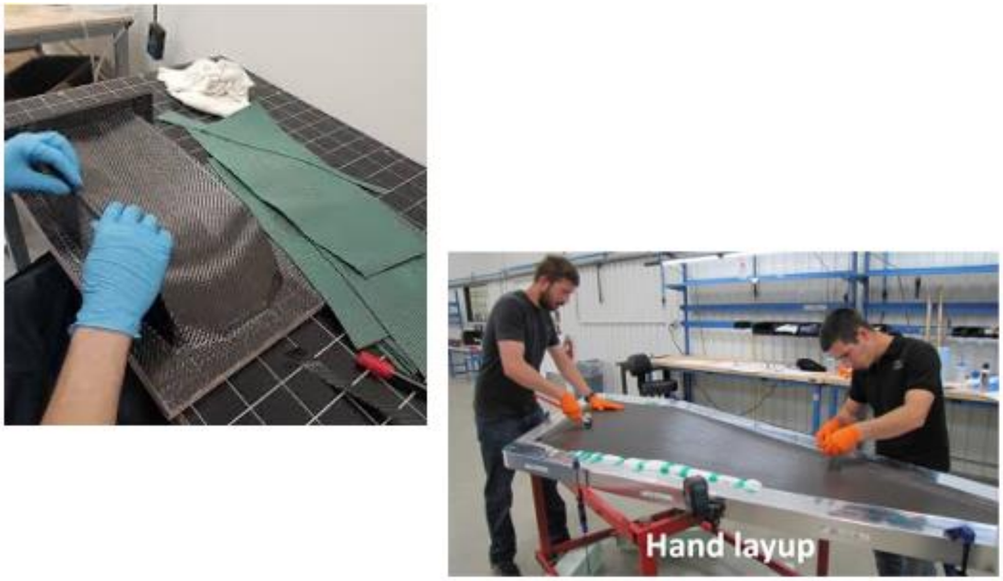


Figure 78 Hand layup of prepreg

After laying and smoothing all the layers in the stack, the next step in the process is bagging. The purposes of this step are to consolidate the layers of prepreg, to allow or encourage trapped air to escape, and to remove the slight excess of resin thereby reducing the weight of the prepreg by lowering the resin content to its optimum level. Lowering resin also means that the fibers carry a higher percentage of the total load and that is also more efficient in strength and stiffness.

A typical bagging assembly is shown in Figure 79.

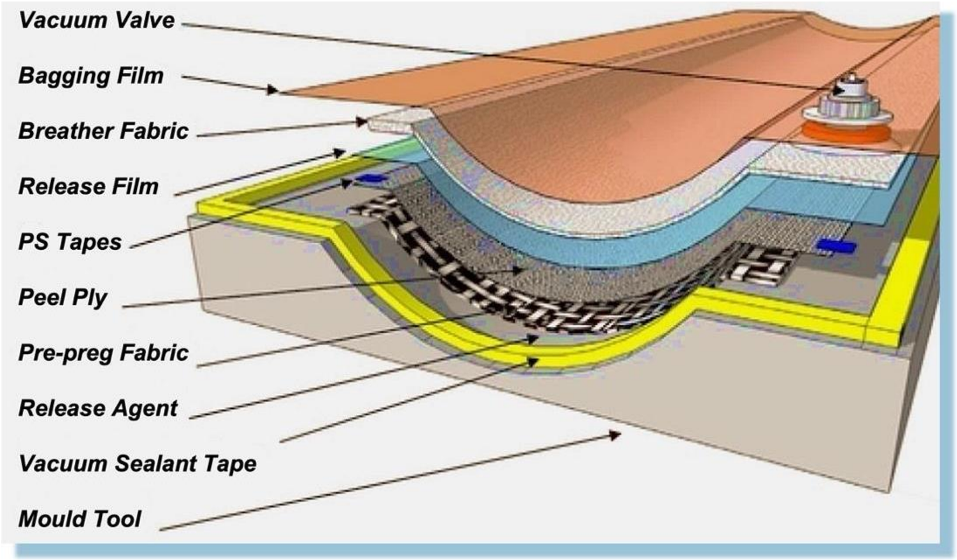


Figure 79 Bagging assembly

Each of the components is described, beginning at the bottom of the assembly.

- The **mold** (mould) tool is the mold that gives shape to the part. Molds are discussed in greater detail later in this chapter. Normally the mold is metal, but composite molds are also used.
- **Vacuum sealant tape** is used to ensure that the bagging film has an airtight seal against the mold. If advanced thermoplastics resins are used in the prepreg, cure temperatures can exceed the stability temperature of the normal sealant tape and special high temperature sealant tapes are required.
- **Release agent** should be coated onto the mold before any prepreg is laid. Release agents are commonly used on all molds, including those used for open molding of fiberglass. These release agents can have many chemical compositions ranging from simple waxes to complex mixtures containing silicone oils and low molecular weight polymers. In some cases, usually fiberglass moldings, the release agent is applied before every molding. In other cases, the release agent is applied to the mold and the mold is heated to allow the release agent to penetrate into the surface pores of the mold and seal it. When this is done, applications of the release agent can be less frequent.
- **Prepreg fabric or unidirectional prepreg** is laid onto the mold surface as specified by the part design. Normally each layer is smoothed and, perhaps, rolled to ensure that it adheres to the under layer. This also helps remove trapped air.
- **Peel ply** provides a simple method of pulling all the bagging system off the part after curing. Generally, the peel ply is a perforated plastic sheet that is strong enough to withstand the pulling action.
- **Pressure sensitive tape (PS tape)** is an inexpensive silicone-based tape used to adhere layers to the mold flanges and also can be used to join bagging film together and to help fit the bagging film to irregular-shaped molds.
- **Release film** assists in the release of the bagging system. The most common material is Teflon□ sheet that has been punched with small holes to allow resin and air to pass through

it. In many bagging assemblies one material (combined in one layer) is used for both the release film and the peel ply.

- **Breather fabric** is an absorbent material that soaks up the excess resin that moves through the bagging assembly during curing. Care should be taken to determine the correct thickness (number of layers) of breather fabric as thicker material will absorb more resin and may absorb so much that some fibers are not fully coated.
- **Bagging film** is usually a nylon film, much like a cooking bag for poultry. The bagging film covers the entire assembly and is tightly sealed to the mold. When the part/mold shape is complex, the film is often tucked with pleats to conform to the shape of the part. If the curing temperature is above about 400°F, nylon film should be replaced by a film with high thermal stability. The most common high-temperature film is thermoplastic polyimide (Kapton□).
- **The vacuum value** is inserted through the bagging film and is screwed together to create an airtight seal.

A typical, completed bagging system is shown in the figure below.

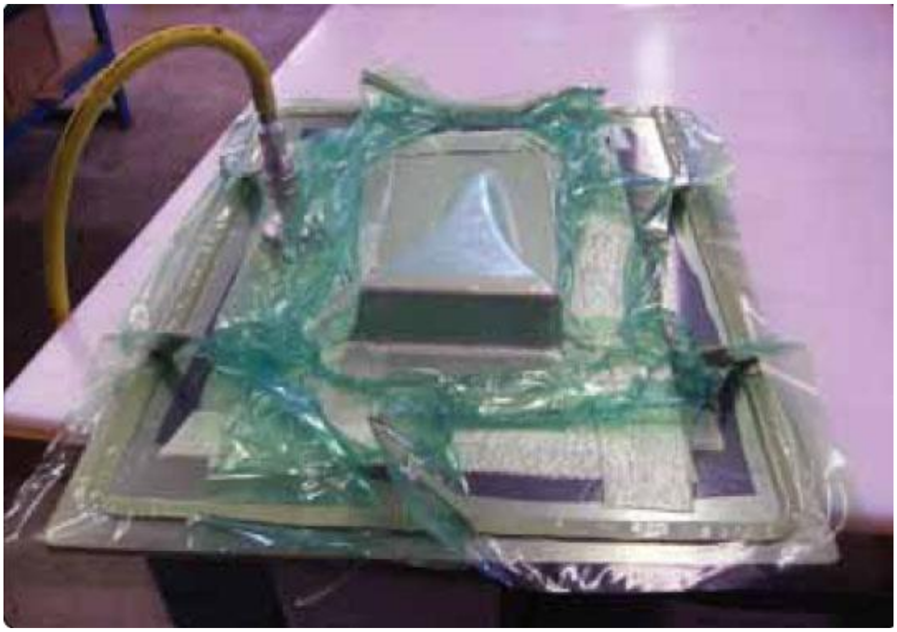


Figure 80 Bagging system

In most vacuum bag assemblies one or more thermocouples are inserted into the system. These are placed through the sealing tape before adhering the bagging film. The thermocouples monitor the temperatures during curing.

If the shape of the part does not allow the bag to compress against the part, perhaps because of a change in vertical dimension, then the bagging film could bridge across the “step.” This will result in incomplete consolidation. To prevent this problem, a semi-rigid rubber material is often placed under the bagging film so that the film will press on the rubber part (called a caul or a pressure intensifier) and the caul will press against the part.

Another problem with some bagging systems is the escaping of resin sideways rather than upward through the bagging system and into the breather. The resin often tends to flow along the fibers allowing this side leakage to occur. The problem is that this does not sweep out the air that might be trapped inside the layers of prepreg. To prevent this from occurring, a border of solid rubber, called a resin dam, is placed around the edges of the prepreg layup. The resin dam, pressure intensifier, and pleated vacuum bag are shown in Figure 81.

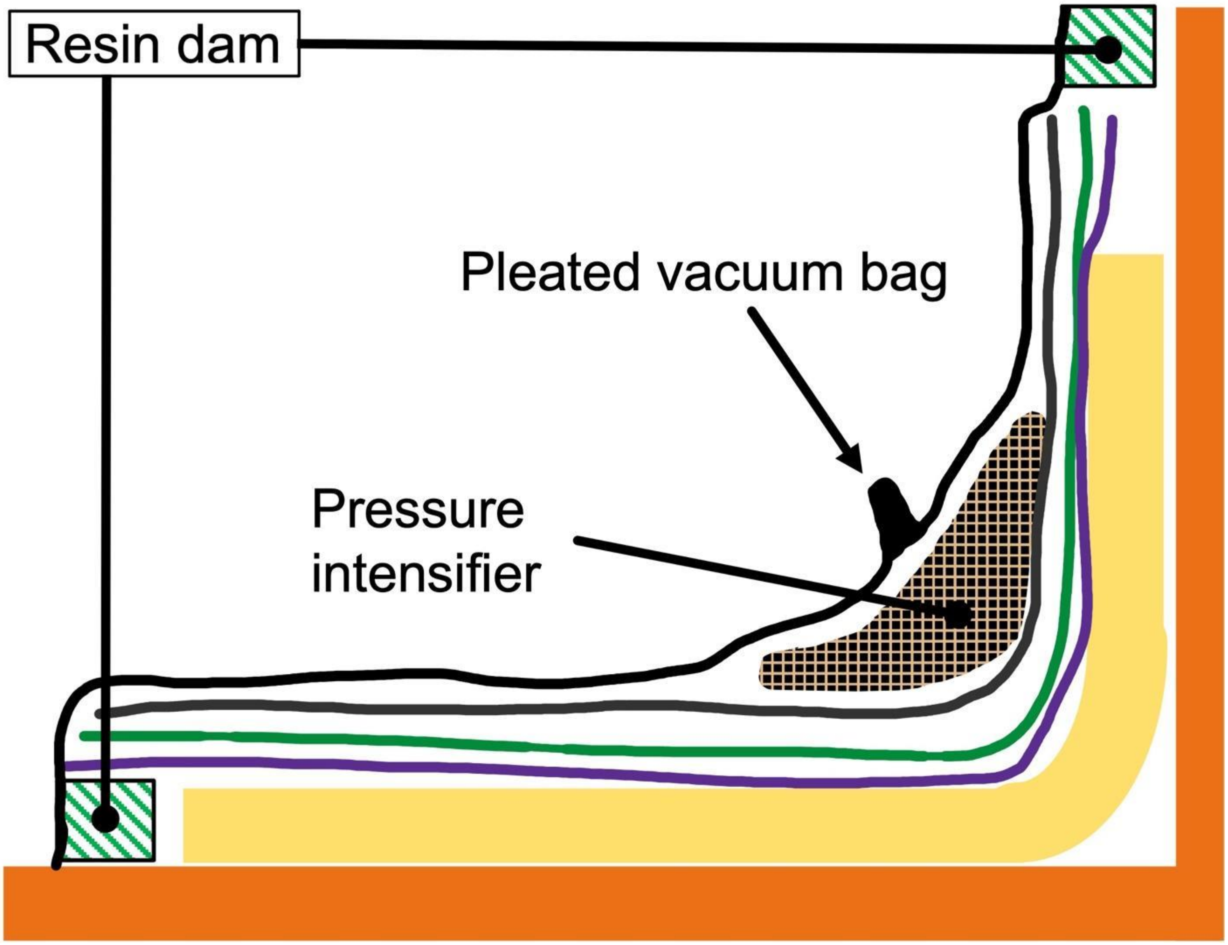


Figure 81 Bagging system with resin dam, pressure intensifier and pleated bag

Manual layup of prepreg is not only highly labor intensive, but for large parts, such as an airplane wing or body section, reaching into the center to properly place the prepreg is very difficult. To solve these problems, automated machines have been invented to lay down both prepreg tape (tape laying machines) and prepreg tow (fiber placement machines). Tape is faster to lay down than tow because more surface is covered with each pass, but if the part shape is complex, the tape may not be able to fit into the complexity and so tape must be used.

The complexity of some parts requires that the placement heads of these machines be able to turn in many different directions and with many different angles. This is called having many axes of movement. (Sometimes as high as nine axes are controlled by the same type of electronic controller as a sophisticated robot.) In fact, some of the latest developments of fiber placement and tape laying machines use robots. Although the machines are quite expensive, they can pay for themselves if the number of parts to be built is high enough. Airplane wings, tails, and bodies are the most common products using these machines. A typical machine is shown in the accompanying figure.

Figure 82 Tape laying machine

Autoclave Curing

Curing a prepreg system is best done with both heat and pressure. The bagging system applies some pressure and heat can be applied within an oven, but for advanced composites, greater pressure is needed and so an autoclave is used in addition to the bagging system. Autoclaves are large (sometimes enormous) pressure cookers into which the mold and all the bagging system are placed and then heated under pressure. A medium-sized autoclave is shown in the figure below.

Figure 83 Autoclave for curing

A typical molding cycle begins after the part and the mold assembly have been put into the autoclave and the door sealed. The vacuum is started to consolidate the part and to check to make sure that the bagging system is airtight. After some time, the heat and pressure of the autoclave are started. The heat is raised at a moderate pace (1-5°F/minute) to give the assembly time to equilibrate throughout. At about 130°F (for typical epoxies), the temperature is held constant so that the resin, which has reduced viscosity at this temperature, can migrate out of the part into the bagging system, taking trapped air with it. After a few minutes, the temperature is then raised again to reach 350°F, the normal curing temperature for high performance epoxies. After at least 120 minutes at this temperature, the part is cooled and is then removed from the autoclave.

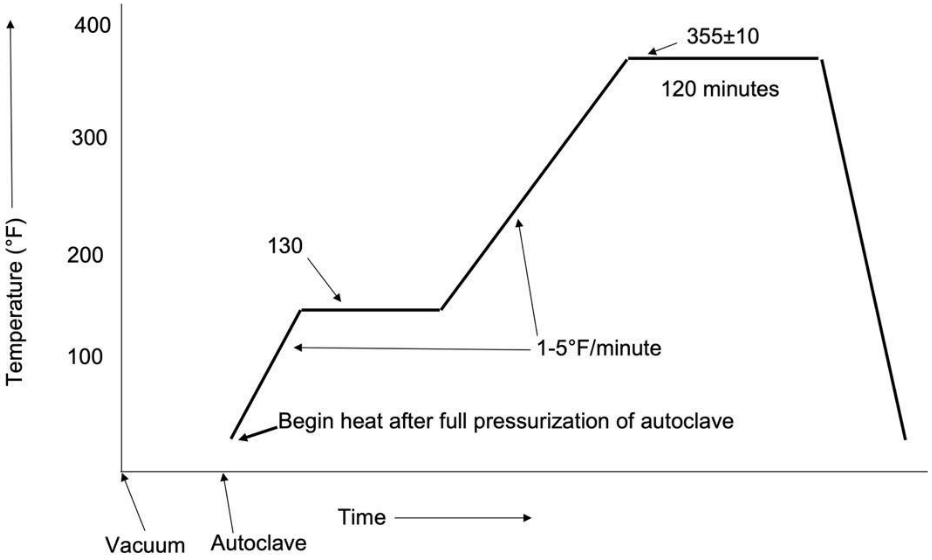


Figure 84 Typical curing cycle for a high-performance epoxy

Roll-Wrapping or Tube Rolling

This is a method to make cylindrical parts without the need of a bagging system or an autoclave. It is used extensively to make tubes and even tapered parts like golf club shafts. This method uses a mandrel, usually a steel rod that is the length of the intended part. Prepreg material is cut into pieces that are as long as the part and are about three times as wide as the diameter of the mandrel. If the mandrel is tapered, as it would be for golf shafts, the prepreg pieces are wedge-shaped so that when wrapped around the mandrel, the fibers remain aligned with the length of the shaft.

An edge of one prepreg strip is pressed against the mandrel so that it is stuck to the mandrel along its entire length. The mandrel is then rolled so that the prepreg wraps around the mandrel and sticks to itself as it goes around. This results in about three layers of material on the mandrel. Other prepreg pieces are added in the same way—sticking one edge to the previous layers and then rolling to wrap around. In this way the designed number of layers is put in place.

Roll-wrapping machines have been developed to automate the rolling and wrapping of the prepreg. After the edge of the prepreg is adhered to the mandrel, the machine closes and the padded top plate and padded bottom plate close on the mandrel. The top plate then moves backward relative to the other plate, causing the mandrel to turn and the prepreg to wrap around.

Figure 85 Roll wrapping operation

After all the designed layers have been applied, a layer of plastic shrink tape (like cellophane) is wound around the outside of the prepreg layers. The wrapped mandrels are then hung vertically in an oven and heated to cure the prepreg. When heated, the overwrap tape shrinks and compresses the prepreg layers giving the consolidation needed.

After curing, the shrink tape is removed and the mandrel is extracted from the center of the cured part. The outer surface of the part will show the lines from the shrink tape and these are usually removed by sanding or grinding.

Closed Mold Processes

In the most common closed mold process the two-part mold closes on the uncured composite material and consolidates and shapes the material as well as applying heat to cure the part. Other closed molding processes force the uncured material against the closed mold and heat is applied to cure the part. Both types of closed mold processes will be discussed.

Compression Molding or Matched-die Molding

During this process a specific amount of uncured composite material—the charge—is placed into the cavity of a matched mold in the open position. (The two mold halves are shaped to reflect the top and bottom shapes of the desired part.) The mold is closed by bringing the two halves of the mold together, and pressure is exerted to squeeze the composite material so it uniformly fills the mold cavity. While under pressure, the material is heated so that it cures. This process is shown diagrammatically in the figure below.

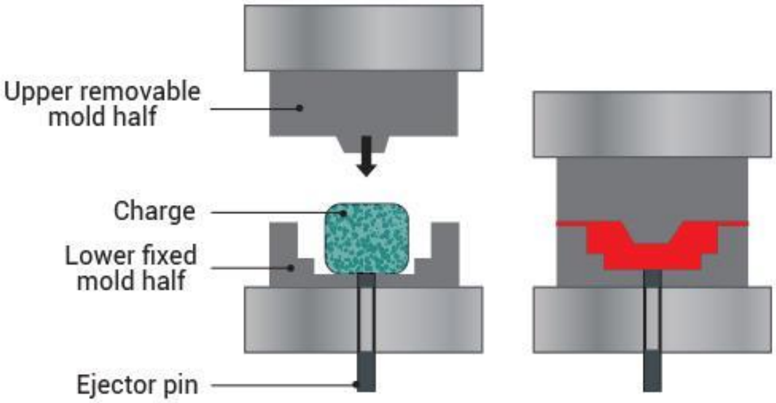


Figure 86 Diagram of compression molding

The molding process can require high pressures and so the molds are mounted in large presses. The presses allow rapid mold cycles and high-volume production. Hence, this process is widely used in the automotive industry and in other industries where high volumes of small-to-moderate-sized parts are manufactured. Part-to-part reproducibility is good, probably better than any other composite manufacturing process. The squeezing of the material results in low void content in the finished parts. The amount of scrap is minimal since the charge can be weighed to just fill the mold.

Compression molding is limited in the complexity of parts that can be produced. For example, compression-molded parts should have few changes in depth. This means that ribs, bosses, and Z-directional shapes (like hats and T-sections) are not practical. Undercuts (where the opening or top of the part is smaller than some dimension below it) are difficult and expensive since they require sliding molds.

Molding compounds, discussed briefly in the chapter on resins, are the most common material used in compression molding of composites. These materials are mixtures of resin, fiber (usually fiberglass), and sometimes filler. The most common molding compounds are prepared in two different ways, each with some clear advantages. The first method is called bulk molding compound (BMC). It is made by simply mixing the ingredients together to make a paste-like material. It is often packaged in a log form so that it can be easily cut and weighed when portioning the charge. BMC is usually dropped into the center of the bottom mold and then flows to fill the mold as the mold closes and squeezes the BMC. To accomplish a uniform flow, the viscosity of the BMC must be correct—not too dry or it won’t fill the mold completely and not too fluid or the resin will move and leave the fibers behind.

Sheet molding compound (SMC) is the other common form of molding compound. This material, also composed of resin (usually polyester) and fiber with filler, is sold in a sheet form. This facilitates loading the mold when the part is wide, as with the hood of a car. To achieve this form, the SMC is made by spreading the resin and/or the resin and filler mixture onto a film (usually about 3 feet wide) and then cutting fiberglass rovings into the length desired (about 3 inches) and allowing them to fall onto the sheet with the resin and filler coated on it. Another layer of resin/filler is placed onto the top to make a sandwich with the fiberglass in the middle. The sandwich is then compacted so that the resin wets the fibers. The entire sandwich is then rolled up and sold. This process is depicted in Figure 87.

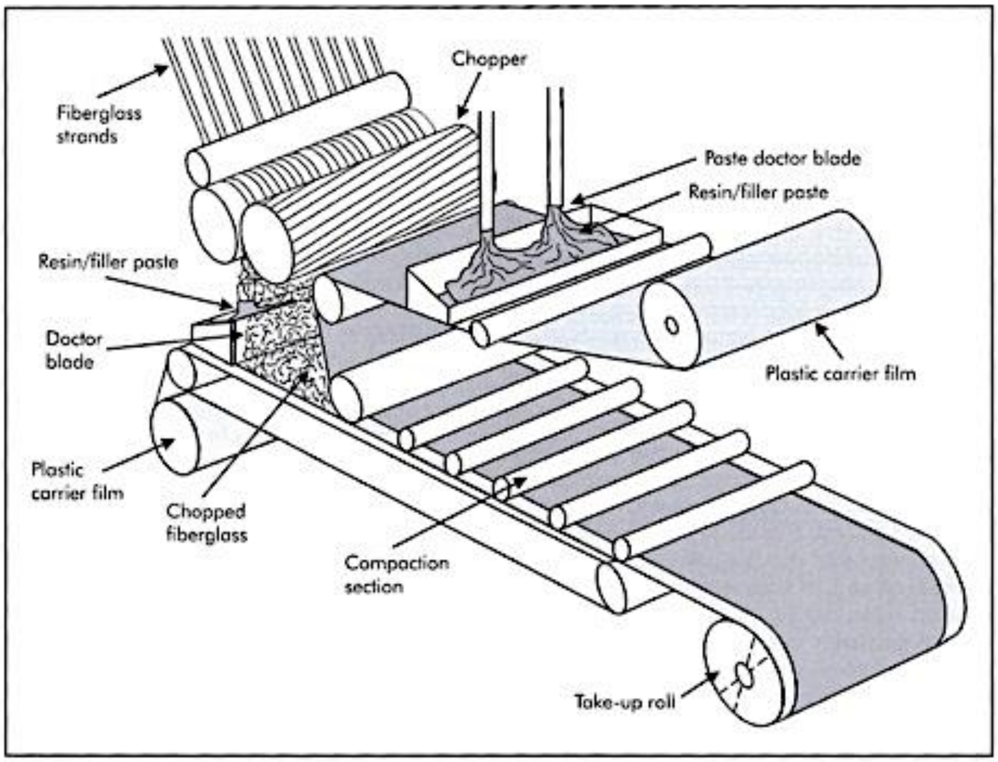


Figure 87 Making sheet molding compound (SMC)

When the SMC is used, the desired amount of SMC is cut off the roll and the plastic sheets removed as the material is laid into the mold. This process was developed to make the body panels of the 1953 Corvette (see Figure 88) and has been used for many automobile body panels since then. SMC has the advantage over BMC that the viscosity is not as critical because the SMC is already approximately the shape of the mold opening. Furthermore, the SMC is usually capable of higher fiber content and that will give better mechanical properties.

Figure 88 Corvette body made with SMC

When viscosity problems exist, such as for a complex part, BMC and SMC might not be able to completely form the part, **preform compression molding** is a good choice. Preform molding is also used when a very high fiber content is desired.

In preform compression molding the dry fibers are preformed to the approximate shape of the part and are placed into the mold. (The fabrication of preforms was discussed in the chapter on fibers.) Resin is added by pouring the resin onto the preform, usually with some effort to distribute the resin over the entire surface of the preform. The mold is then closed, which causes the resin to flow throughout the preform, wet the fibers, and compacts the preform to the shape of the mold cavity. The part cures because the mold is heated.

Because filler is rarely used in preform molding and the fibers can be very long, depending on how the preform is fabricated, this method can be successfully used to make advanced composite parts. The fibers move very little in this process, except for the compacting and so the final shape can be very near the preform shape. The high pressure of compression presses also means that voids are squeezed into very small volumes and the void content is usually very low.

Because the resin is added separately from the fabrication of the preform, a greater variety of resins is possible. Epoxies are common, as would be expected. Other resins frequently used include phenolics. An important point to remember with phenolics is that when this resin crosslinks, water is formed in the reaction. This water should be allowed to escape (usually as steam because the press is heated). The method employed to allow this water/steam to escape is to open the mold very briefly during the curing cycle. This process is called bumping the mold or breathing the mold or, less often, burping the mold.

Another variation of matched die molding that works well for advanced composites is **prepreg compression molding**. In this method cut prepreg strips are placed into the mold and then compression molded. Fiber-resin contents are, of course, set by the prepreg manufacturers. The fiber lengths can be as long as the entire length of the part. Fiber orientation is controlled by the lay-up of the stack within the mold and by the closing of the mold. Some minor fiber movement within the mold is common. However, with careful design of the mold cavity and the lay-up stack, in-mold movement can be minimized. Therefore, properties of prepreg-molded parts can be excellent.

Normal prepreg molding is essentially a manual lay-up process and can, therefore, be used to make parts that contain inserts like metal rings for attachments, hinges, and labels. The inserts can be placed at the same time as the prepreg material and the prepreg will be shaped around the inserts. During molding, the prepreg flows to create a smooth boundary attachment and gives good bonding to the insert.

When lower properties are acceptable, the prepreg material can be chopped and then placed into the mold. This gives a reasonably random orientation to the fiber. Of course, the fibers are shorter than when the prepregs are stacked manually in the mold and properties are lower than for full-length fibers. However, the chopped prepregs can be placed in the mold by semi-automated methods. Therefore, the labor component of the molding costs can be substantially reduced. If needed to facilitate movement of the chopped pieces in the mold, some additional resin can be added.

A rapidly growing area for compression molding composites is the use of **thermoplastic resins**. The starting material for this process is almost always thermoplastic prepregs. These prepregs are made by melting the thermoplastic resin (because it is a solid at room temperature) and then applying it to the fibers or, alternately, covering the fibers with a sheet of extruded thermoplastic resin or with powdered thermoplastic and then pressing and heating to infuse the thermoplastic resin into the fibers.

The thermoplastic prepregs can be laid into the mold with the desired directionality of the fibers just as thermoset prepregs. However, many composite part manufacturers who use thermoplastics modify the system slightly by creating a semi-finished stack (called blanks which are equivalent to kitting in thermosets) and then heating the stack enough to partially melt the resin and bind the layers together. This can be done on a conveyor system with high volume. Then, when the parts are to be made, the blanks can be preheated to reduce the molding time and conveyed into the compression molding press where they are further melted and consolidated. Typically, the time in the compression press is only a few seconds. This process is illustrated in Figure 89.

The advantages of this system are much shorter molding times, the ability to automate key processes and the general advantages of toughness and other properties of thermoplastics. This process holds great promise for use in the automobile industry and may find applications for relatively small parts in the aerospace industry.

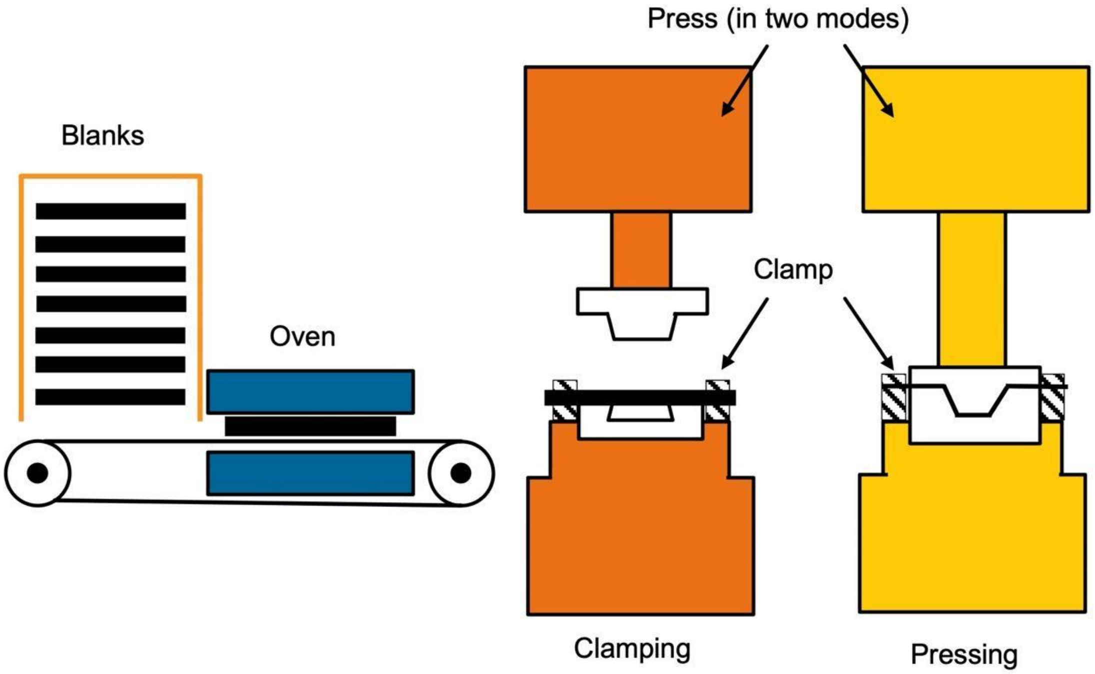


Figure 89 Compression molding thermoplastics

Clamshell Molding or Bladder Molding

Autoclaves and compression presses are not the only methods for applying pressure to a composite laminate. An example of an alternate system is used in making tennis racquets and forks on bicycles and other parts where shapes are difficult to mold, the part is hollow, and the outside of the part needs to be an appearance side.

This method begins by wrapping prepreg around a bladder that is inflated so that it is semi-rigid. After the correct amount of prepreg material has been wrapped around the bladder, the assembly is placed inside a two-part mold that resembles a clamshell. (It might even be hinged.) This mold need not be made of thick steel as the pressures it will experience are much less than the pressures of compression molding. The mold is designed to define the outer surface of the part when it is pressed against the inner surface of the clamshell mold.

The mold and prepreg assembly are placed inside an oven and heated while pressure is added to the bladder. This internal pressure forces the prepreg stack against the inner mold surface where it is cured. Normally the clamshell mold interior diameter is only slightly larger than the prepreg assembly, thus minimizing the movement of the fibers. When the part is cured, the pressure on the bladder is released and it collapses and is removed from the interior of the part or, perhaps, just left in place.

A clamshell system was used to make the fuselage of the Starship airplane (prototype) in 1986. The entire fuselage was made in one piece over a 24-hour continuous run. The results were excellent.

The clamshell molding system is excellent for making parts that are hollow and complex in shape. A part shown in Figure 90 was made by the clamshell method and illustrates the complexity that can be achieved.

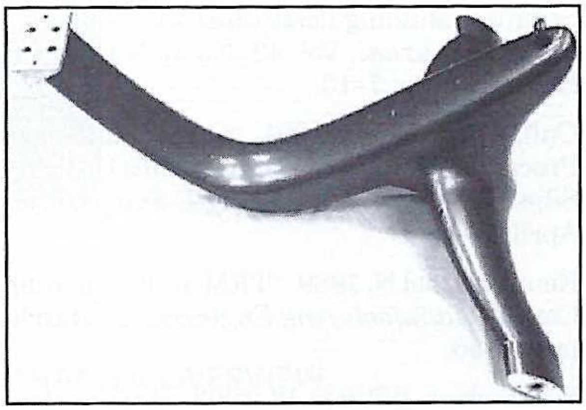


Figure 90 Part made by bladder molding

Trapped Rubber Molding

This process is similar to clamshell molding except that rubber (usually silicone) is used in place of the bladder. The silicone has an internal cavity that is shaped like the outside of the intended part. The prepreg is laid up on a metal mandrel that is placed inside the silicone and then the entire assembly is placed inside a mold. The interior dimensions of the mold closely match the outer size and shape of the silicone. The exterior mold is heated and it then heats the silicone. The silicone expands and pushes inward against the prepreg stack. The prepreg cures and the heat is turned off and the silicone shrinks back to its starting size. This allows the part to be extracted.

Resin Infusion Processes

Several variations, discussed below, have been developed for the resin infusion process but all share some basic features. The dry (without resin) fiber (usually a preform) is placed in the mold and the mold is closed. Resin is then injected into the mold so that it fully wets the fiber. The resin is cured by heating the mold, the mold is opened, and the part is removed. The process is diagrammed in Figure 91.

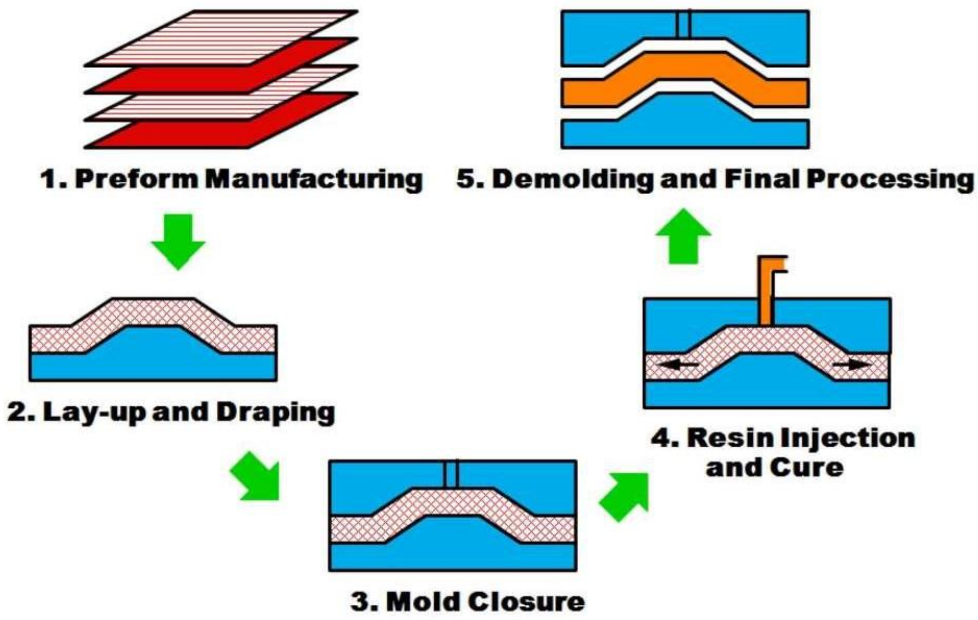


Figure 91 Resin infusion process

The advantages of the resin infusion processes include ability to use continuous fibers with generally little fiber movement (thus permitting the use of the process for advanced composites), lower emissions of volatile components (especially important with unsaturated polyester resins), little requirement for machining or other finishing after molding, low requirements for auxiliary equipment (like freezers and autoclaves), flexibility in size and part complexity, generally short cycle times, high repeatability, the ability to place inserts into the mold before closing, and the ability to co-cure parts that would otherwise be separate, thus reducing the total number of parts in an assembly.

The major disadvantages are ensuring that the fibers are all fully wetted, the need for special resins with low viscosity, and difficulty in removing of all the entrapped air.

Resin Transfer Molding (RTM)

RTM is the most widely employed of the infusion techniques and the name is sometimes used for all infusion processes. This process is distinguished from the other infusion processes because RTM uses pressure to inject the resin. Pressurized injection has the advantage that resin can be pushed through difficult and compacted preforms. Fiber volume contents as high as 70% and void contents as low as 1% are possible. There is more control over the injection process than when only vacuum is used. However, the increased pressures not only mean that the molds must be robust, but they must be held firmly shut. Whereas simple clamps can be used in vacuum infusion processes, RTM requires more extensive closure devices. Some manufacturers simply put the RTM mold in a compression press to hold the mold halves together.

Vacuum Infusion Processing

Vacuum infusion processing uses a vacuum to pull the resin into the fibers as opposed to the pressure system of RTM. Normally the vacuum is applied simultaneously at several strategic locations where the resin is likely to fill last. When applied at multiple locations, each vacuum tube can be pinched off when the resin is observed to arrive at that vacuum site.

Because of the lower pressures in vacuum infusion, the molds need not be as robust as in RTM and the clamps can also be simpler and less expensive. It is even possible that one side of the mold can be a vacuum bag. Note that the side next to the vacuum bag will not have a finished appearance.

It is possible to combine pressure filling and vacuum filling. The name commonly used for this technique is vacuum assisted RTM (VARTM).

SCRIMP™™

The full name of this process is Seeman’s composite resin infusion molding process. It is a patented method of resin distribution coupled with the vacuum bag molding process. By means of various manifolds (called omega channels because of their shape), the resin is quickly distributed across the part while the vacuum is applied under the bagging material. The resin then saturates the fibers. Because the resin is distributed quickly, large parts can be made by this process as shown in Figure 92.

Figure 92 SCRIMP process to make a 64-foot boat

Filament Winding

Filament winding has been an important composite manufacturing process since the 1960s when it was used to make the cylindrical cases for rocket motors. It has continued to be an important manufacturing process for both fiberglass and carbon fiber products. Although most of the products made with this process are cylindrical, innovations in winding techniques and machines have allowed the manufacture of closed-end pressure vessels, tapered parts, and parts that are not round (some are almost square).

The basic filament winding process can be understood by referring to Figure 93.

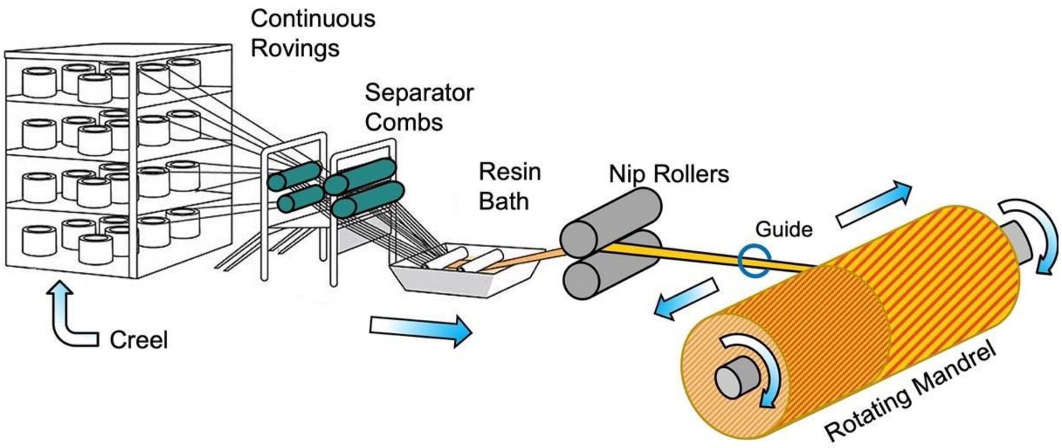


Figure 93 Filament winding process

The fiber spools are mounted on a rack, called a creel, and then strands from many spools are gathered together and fed through a comb or similar alignment device so they make a band of fibers. The number of strands brought together determines the width of the band. The band then enters a resin bath where the fibers are soaked with resin. The resin is fully activated with initiator or hardener so that the only requirements to cure the part are heat and time. The fibers then go through a roller or wiper system to remove the excess resin and then through a ring or some other directing device called a guide or payoff. The guide directs the fibers onto a mandrel (solid or semi-solid tool) that turns as the payoff moves laterally, thus covering the surface of the mandrel with one or more layers of fibers. It is also possible to use prepreg tow instead of dry tow. When this is done, the process is the same except the resin bath is eliminated and provision is made to soften the prepreg when it is placed onto the mandrel so that it will adhere to other layers. If thermoplastic prepreg is used, the thermoplastic layer and, perhaps, the layer underneath should be heated to near melting and applied with pressure.

After the part is cured, it is removed from the mandrel, either by forcing it off mechanically or by collapsing the mandrel. Sometimes the mandrel is made of plaster or some other material that can be broken or dissolved, thus freeing the part. It is also possible to wind onto a plastic or rubber mandrel that has been inflated to the desired shape. These mandrels can be removed by deflating the mandrel, although some thin plastic or metal mandrels are simply left inside the part.

In the case of pressure vessels used for waste tanks on aircraft and some pressure vessels for gas storage such as for hydrogen fuel tanks, the mandrel is usually a thin aluminum shell that is left within the tank. This winding process is shown in Figure 94. To wind the closed ends requires that the guide have several additional axes of motion so that it can move in, out, and sideways as the ends are wrapped.

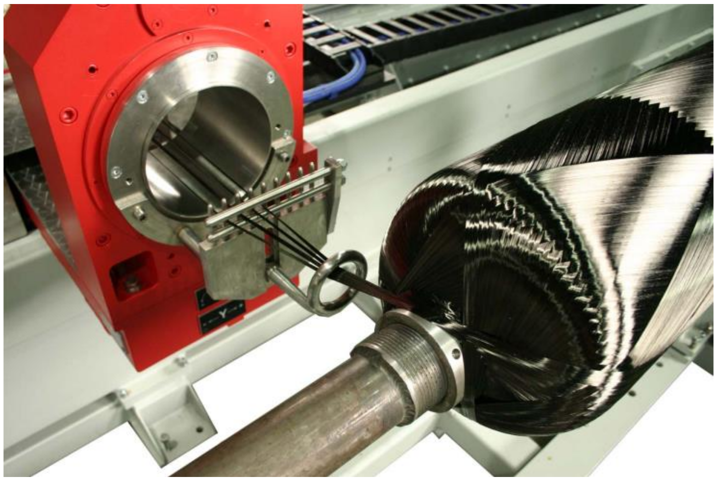


Figure 94 Winding a pressure vessel

Most windings require that the fibers be placed at different angles, analogous to different fiber orientations in a stack of hand layup prepreg. The winding angles have been grouped into three different winding patterns—hoop, polar, and helical—as shown in Figure 95.

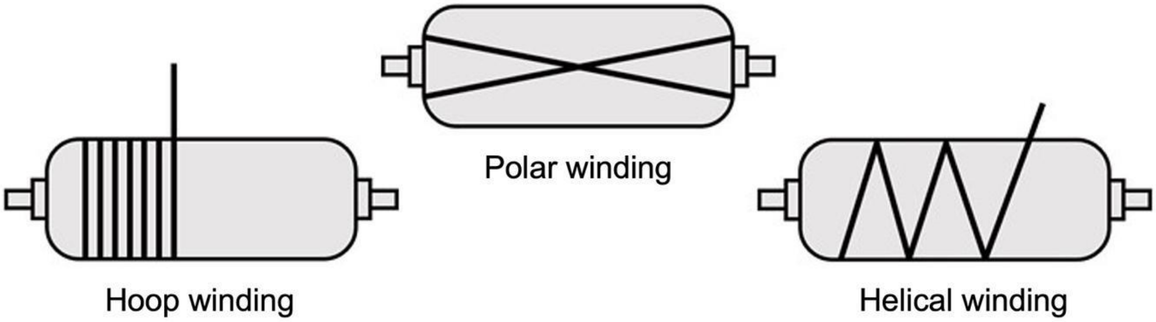


Figure 95 Filament winding patterns

Filament winding is a highly efficient composites manufacturing method in terms of the amount of fiber that can be applied per unit of time. This is possible because the process is highly automated and the shapes are generally simple. To further increase the efficiency, some filament winding machines have the capability of winding several mandrels simultaneously with separate winding guide. This saves capital cost as one motor turns several mandrels, all situated in a single frame. These machines are especially useful for making parts that are reasonably small in diameter such as golf club shafts and pipes.

Pultrusion

Pultrusion is another composite manufacturing system that is very efficient in terms of pounds of fiber deposited per minute through the machine. Like filament winding, the shapes made by pultrusion are relatively simple, thus allowing for the high production rate. An illustration of the pultrusion process is given in Figure 96.

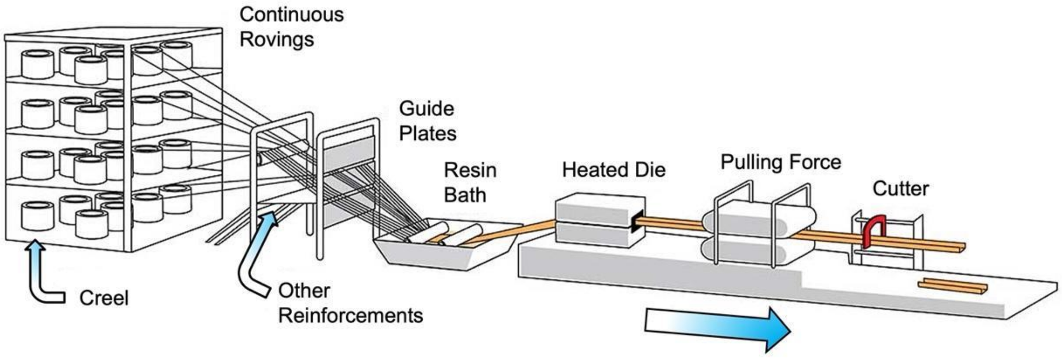


Figure 96 Diagram of the pultrusion process

The pultrusion process begins with continuous fibers being drawn from reels and formed into a general shape that allows for orderly movement into the resin bath. If desired, additional reinforcements, often mats or cloth, can be directed into the reinforcement preform to include some fibers in a direction other than just the machine direction. The fibers are wetted by the resin and then are further formed as they converge toward the final shaping die. The wetted reinforcements then enter the heated die where they are forced into the final shape and cured. Upon exiting the die, the formed (cured and hardened) part enters the pulling system. The puller provides the force for movement of material through the entire system. Then, the pultruded part is moved to a cutter and trimming station where finishing processes are performed.

Because the parts are formed in a die and are fully cured when exiting the die, only parts with a constant cross-section shape are made by pultrusion. Some typical pultruded parts are shown in the Figure 97.

Figure 97 Typical pultruded parts

Molds and Other Tooling

Composites are molded in order to give the matrix the shape desired. Therefore, molds are an important part of every manufacturing process. A brief review of molds is appropriate here with some discussion of what needs to be considered in choosing and using molds.

Molds can be convex (male molds) or concave (female molds) or some combination of the two when the part is especially complex. Figures 98 and 99 show both types of molds.

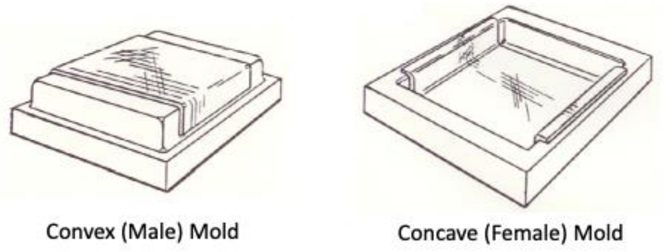


Figure 98 Diagrams of types of mold shapes

Figure 99 Production molds

These different mold shapes have some differences in layup difficulty. It is much easier to lay up prepreg over the outside surfaces of a male mold than into the corners or deep draws of a female mold. Furthermore, the sharpness of the curvature going into corners or around edges that is permitted is different. For convex molds the radius of curvature can be quite small (about 0.1 inches), whereas with concave molds the radius of curvature must be larger (about 0.3 inches).

Another consideration is the difference in expansion when heated (called the coefficient of thermal expansion or CTE) of the mold and the composite part to be formed on the mold. When the mold is metal, the coefficient of thermal expansion will be greater than the CTE of the cured composite part. If the mold and heating cycle are not designed properly, the expanding mold might press against the cured composite part and crack the part. This possibility is especially a problem in a male mold where the mold is inside the composite part. To prevent this, design of the part must be robust and temperatures carefully controlled during cure. With female molds, the differences in CTE of the mold and the part might lead to premature separation of the part from the mold as the mold expands away from the composite part and, consequently, a part with poor surface quality and possibly incomplete compaction.

This discussion of CTE differences leads to a consideration of mold materials. The CTE difference problem can be bypassed if the mold is made of composite, thus duplicating the CTE of the part. Composite molds have the drawback that they are not as durable as metal molds. Therefore, if the number of parts to be made is small, composite tooling is a good choice but if many parts are to be made, using composite molds may require that several molds be made during the entire production of the parts. Also, composite molds can be porous (if not properly sealed with a sealing resin) and that can cause roughness on a part surface. Therefore, care should be taken to thoroughly coat both the face and the underside of a composite mold with a sealing resin.

Another method of bypassing the CTE problem is by using Invar, a steel alloy that has nearly the same CTE as carbon fiber composite. The difficulty with Invar tooling is that the cost of making the tool is very high (perhaps double a regular steel mold) and the delivery time can be very long because of the shortness of supply of Invar and the difficulties of making the mold with this material. However, when high volumes of composite parts are expected, such as for the Boeing 787 or the Airbus A-350, Invar tools are the norm.

Other considerations include the thermal mass of the tooling that might require adjustments in the mold time to ensure that the entire assembly reaches the desired temperatures, the degree of accuracy required on the surface to ensure mating of the composite part with other parts of an assembly, and the need for draft angles, that is, the small (0.0005 inch) opening on “straight” sides that is needed to permit the part to be removed from the mold.

Adhesive Bonding

A major advantage of composites over metal parts is that composites can be adhesively joined. This can result in much faster production times when joining is used instead of metal fastening with rivets or other mechanical joining. If done correctly, adhesive joining can also result in stronger assemblies than when the assembly is joined with rivets. (The holes made to allow for rivets break the length of the fibers and create places where cracks can initiate.) However, adhesive joints are more difficult to inspect than mechanical fasteners and, as a result, the Federal Aviation Administration (FAA) has not certified adhesive joining for many of the critical joints on commercial aircraft. These aircraft joints are still riveted together. Sometimes they are both riveted and adhesively joined. Even with these restrictions, many parts of the aircraft are adhesively joined as shown in Figure 100.

Figure 100 Adhesively joined parts on an A-350

Many other composite parts such as skis, bicycle components, composite bows, artificial feet, and drones are adhesively joined. To ensure that these parts are properly joined, some considerations are important.

- Adhesion depends on the formation of chemical bonds across the interface surface. Therefore, ensure that the adhesive is compatible with the composite material.
- Surfaces of the composite must be clean and dry so that there is no interference between the adhesive and the composite surfaces.
- Application of the adhesive should be uniform. To ensure this, most adhesives used in aerospace are sheets.
- The adhesive must be cured to complete the cross-surface bonding. This often requires heating as the adhesives are often thermosets.

Finishing

Most composite parts need some trimming, drilling, or smoothing after the part is removed from the mold. When the amount of finishing is small, mechanical methods are the norm. Air driven hand tools, wet saws, computer numerical control (CNC) routers, and machining centers are often used. Special tooling, called jigs and fixtures, are often used to hold the composite part while these finishing operations are being done.

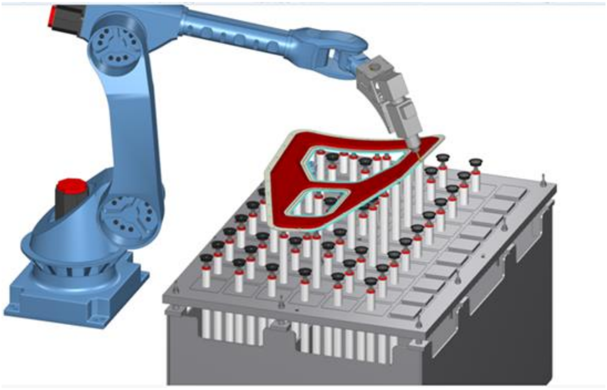


Figure 101 Composite finishing with a robot and holding fixture

Mechanical cutting, drilling, etc. of composites have some difficulties that are not encountered with metal parts. Because the composites consist of two different materials—a very hard reinforcement and a softer matrix—machining is difficult. Cutting bits and other tools wear out much more quickly than when normal cutting of a metal is done. Moreover, some fibers, especially aramids, are so tough that they pull when cut and tend to leave a ragged edge. Therefore, special materials for cutting tools (sometimes diamond encrusted) and special cutting tool shapes are sometimes required.

Another way to solve most of the cutting problems is to use a waterjet cutter. These machines boost water pressure very high (to about 50,000 psi) and then squirt the water through a nozzle onto the part. Waterjets successfully cut most composites without problems. However, the waterjet machines are quite expensive and some small shops cannot afford them.

Figure 102 Waterjet cutting

Quality Control

Composite parts are often inspected after each major manufacturing step. The most common inspections are for dimensional accuracy (size, thickness, shape, etc.) and for general appearance. Tests for strength and other mechanical properties are generally done with prototypes and test coupons before full production is begun because these tests are destructive and the composite parts are so expensive that destroying them for testing does not make economic sense. However, the strength and stiffness depend on how the fibers are applied, and that sequencing of the layers and accuracy of placement are often inspected as the layers are being laid down.

Several inspection methods have been demonstrated for finished parts, but the most common is ultrasonic testing. In this method an ultrasonic signal is sent through the composite part and the time for the echo of the signal is noted. (The signal will always bounce off the opposite side of the composite and return to the receiver that is mounted with the sender head.) If the signal returns too quickly, then some interruption in the composite must have occurred and that is noted as a defect. The interruption could be a gap between layers or some foreign object that has been trapped in the composite.

Because the ultrasonic signal is very rapidly diminished when passing through air, a spray of water between the head and the part or complete immersion of the part in a tank of water are usual methods of carrying out the ultrasonic testing.

To ensure that the entire composite part is properly made, the ultrasonic test scans the entire surface of the composite part. Hence, the normal system for doing this test is to mount the ultrasonic head and receiver on a robot that is programmed to do the scanning. This is shown in Figure 103.

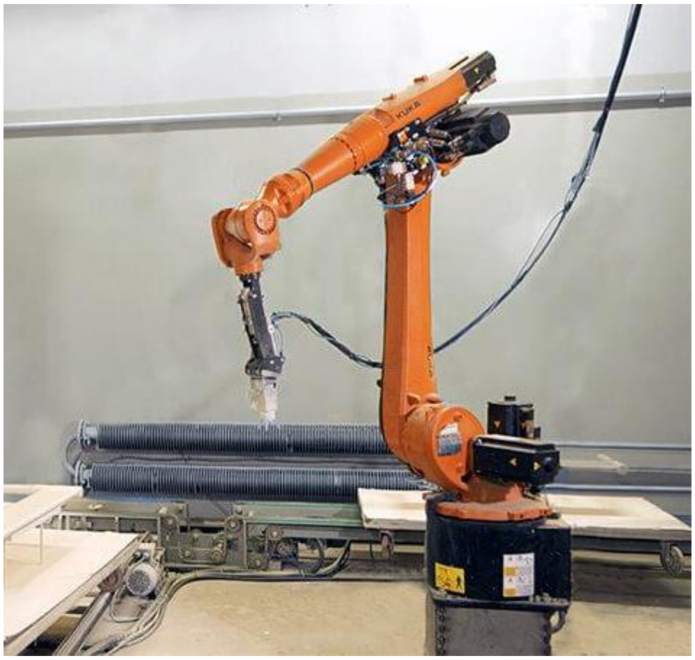


Figure 103 Ultrasonic testing using a robot and water spray

Comparing Composite Manufacturing Processes

If you were to have a new product and wanted to decide which of the composite manufacturing processes you should choose, several considerations would enter into that decision. The first might be which process or processes are appropriate for making that product. Another consideration might be which processes do you or your company have available. Still another could be which process can you afford if you have to buy one. Still another consideration could be which of the appropriate processes is the least expensive to run. The following chart shows the cost per part for various processes. Each of the principal manufacturing costs—labor, equipment, tooling, and material—are shown in the chart. In general, pultrusion is the lowest cost process, followed by filament winding but those have the greatest restrictions on part shape.

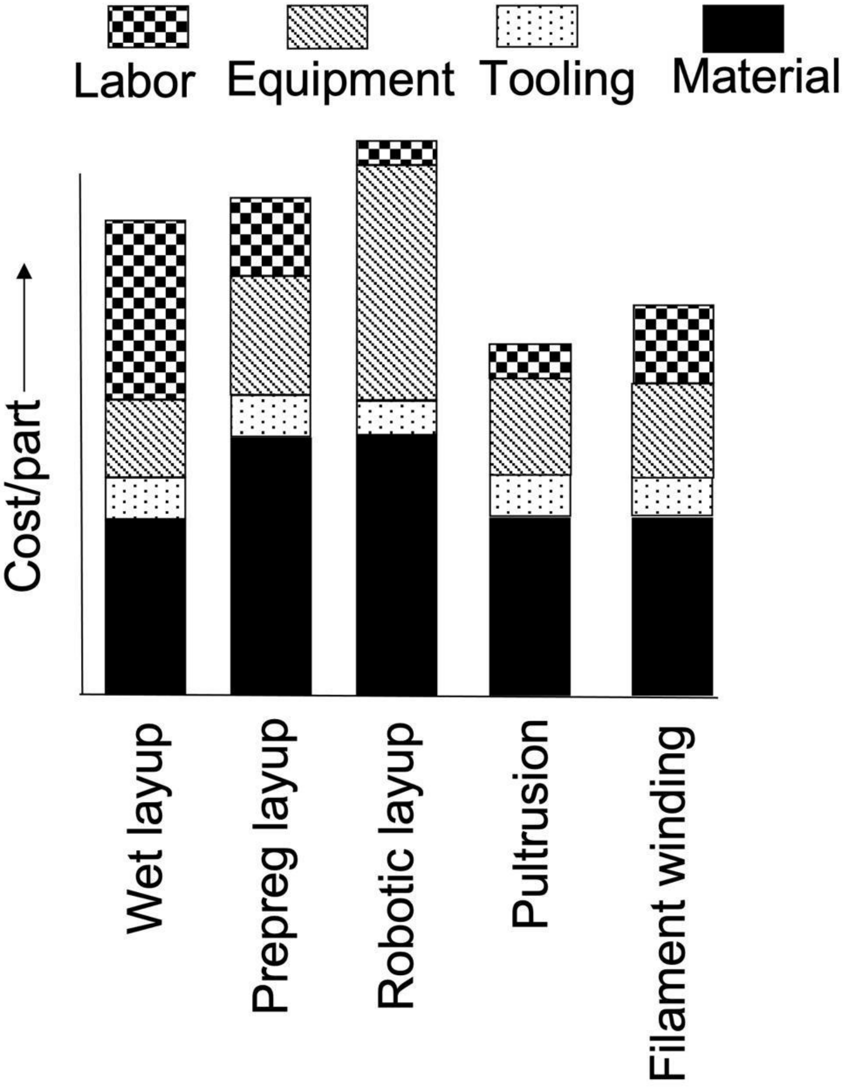


Figure 104 Cost comparison of manufacturing processes

Another consideration could be the cycle time for each process. This is especially important when the volume of parts to be made is high. This comparison is shown in the chart below. Pultrusion has the shortest cycle time as would be expected from a highly automated process. As the processes become more manual, the time increases as shown in Figure 105.

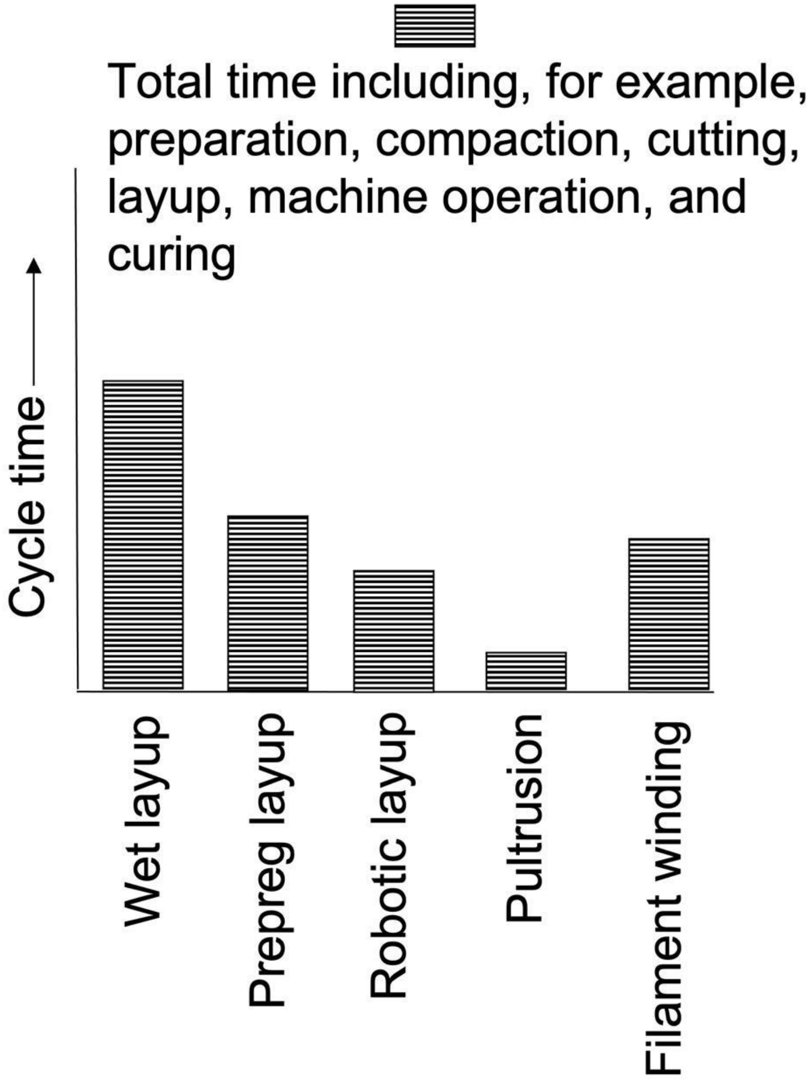


Figure 105 Cycle time comparison for several processes

The rate of laydown of the composite fibers and the complexity of the composite part can be related and are dependent on the process chosen for doing the manufacturing. This relationship is shown in Figure 106. Note that automated tape laying has the fastest laydown rate but has a relatively low ability to make complex parts. Hand layup is the opposite as would be expected of a highly manual process.

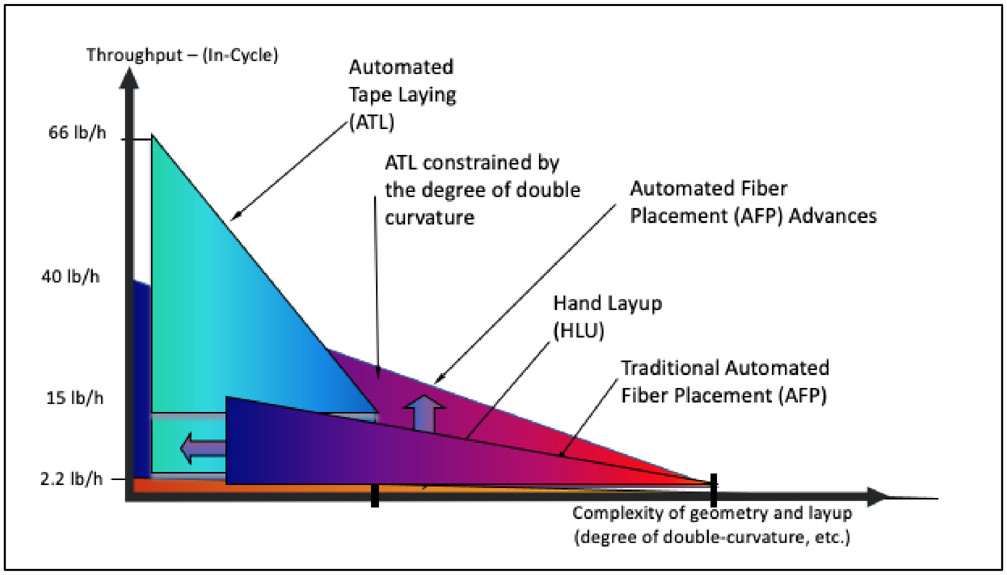


Figure 106 Laydown rate and part complexity relationship for several processes

One more consideration on process choice could be the experience of other companies in the same field or making similar products. The overall use of several composite processes is shown in Figure 107. Of course, processes used in the automotive and other very high-volume industries have greater use.

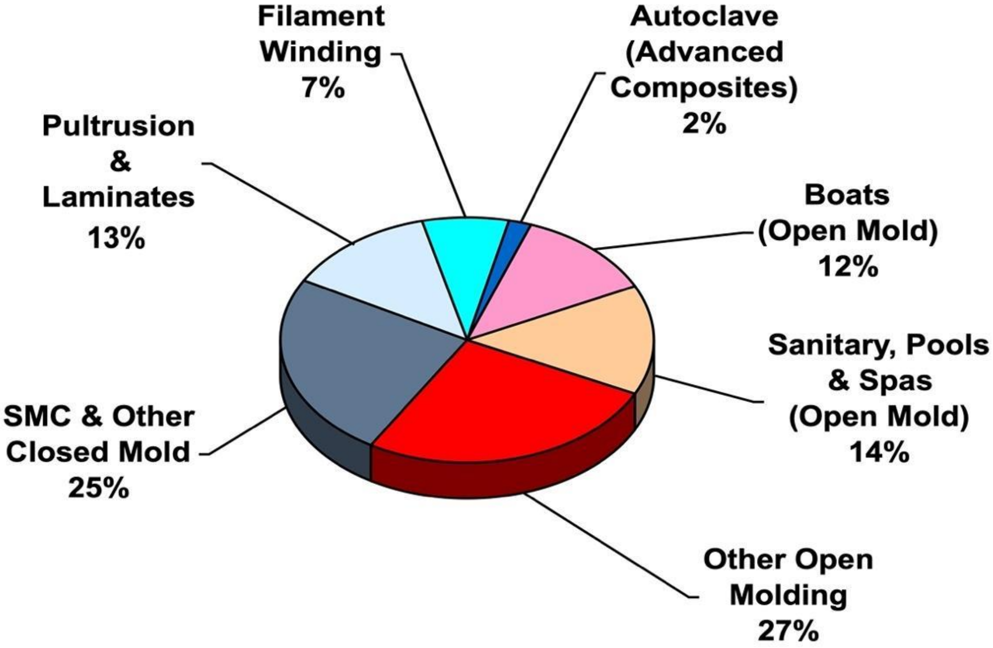


Figure 107 US composite markets by fabrication method

Fun Activity

Objective: Make a composite part of your choosing or enter the SAMPE bridge-building contest. (Note: These procedures will assume you are building a bridge for the contest but you can modify the procedures to fit another product, as you wish.)

Procedure:

1. Contact the Society for the Advancement of Materials and Process Engineering (SAMPE) and ask them for assistance in obtaining the materials and equipment needed for this project. The SAMPE website is SAMPE.org.
2. Based on information from SAMPE and your own desires and the equipment and materials available, decide what type of product you want to make. We will assume you are making a bridge.
3. Design the bridge by deciding on the bridge dimensions (check the contest rules) and the type of structure you wish. Decide on the number of layers in each section of the bridge and the directions of the fibers.
4. Obtain the materials from which you will make the bridge.
5. Lay-up the materials according to your design.
6. Become familiar with the operation of the equipment you will use to cure the bridge and then do the cure.
7. Remove the part from the mold and making any trimming necessary.
8. Weigh the part.
9. Test the part's strength according to the rules of the contest.

Some examples of bridges from the contest are shown below.

Figure 108 Bridges for student contest

Figure 109 Bridges for student contest

Chapter 7 — Composites Recycling

Just as composites are more complicated to manufacture than metals or plastics, they are also more complicated to recycle. However, all composites can be recycled (at least in theory) using the methods described in this chapter. The high value of the components in composites, especially the fibers, and the need to avoid putting additional materials into landfills have spurred several companies to develop composite recycling systems that are both profitable and environmentally appropriate. These recycling methods have different goals and are vastly different in execution. Each of those methods currently being used will be discussed separately. Of course, new recycling methods will be developed as more and more composite parts reach the end of their useful life.

Using these various recycling methods will allow all composites to be recycled, although the overall costs of recycling using some methods are much different from others. The total cost of recycling is the cost of the recycling method less the amount of profit earned from reselling the reclaimed components. In all methods, the costs of transporting the waste composites and of depositing them in landfills is always saved. There are usually some costs to transport the composite to the recycling company.

Goals of Recycling Composites

The goals that govern how composites are recycled depend to some extent on the needs of the company making the composites parts (and creating the waste composites) and also on the recycling company that hauls the waste away, recycles the product, and finds suitable applications for the recycled materials. These goals can be summarized as follows:

- Reuse composite parts with little or no modification. Lowest cost and most direct solution. Generally, this is an end-of-life solution.
- Recover the fibers and the resin with no loss of properties in either one. This will allow high value applications where the excellent properties of fiber and resin can be fully utilized.
- Recover the fibers with no loss of properties but not recover the resin. This allows fibers to be used in high value applications but requires that the resin be disposed of with no pollution.
- Chop composite parts and possibly combine with added resin and mold to moderate-value applications.
- Use fiber and resin without separation. This may require a lower value application but saves money in recycling.
- Avoid landfill with any application even when the properties of the composite components are not fully utilized.

Reuse with Little or No Modification

Some composites are readily recycled as full assemblies, that is, the whole composite part is removed from one purpose and used in another. For example, when an airplane reaches its useful life in terms of total miles or cost of maintenance for passenger traffic, the planes are sold to companies that use them for freight and other non-passenger applications. This is also done with automobiles and a host of other products.

When the parts reach their ultimate end-of-life state and cannot be used for their original purpose, then the composite assembly must be broken apart from non-composite components. Because composites have been put together in the beginning to be very durable and to resist being taken apart, this task is quite difficult, especially if the separate parts are to be used without major reworking. In practical terms, the assemblies are usually no longer useful as complete parts and are chopped or otherwise reduced to easily handled sections that are recycled using one or more of the methods discussed below.

This end-of-life status for composites has not yet been a major problem because most composites are still in their original life service. However, as composites become more widely used, and time passes, new strategies for end-of-life recycling will likely be developed.

Recover Fibers and Resins

The values of new, never used, fibers, especially carbon fibers, are currently about $15 per pound for most carbon fibers and for some the types of carbon fiber are over $50 per pound. Strong efforts are being pursued to lower the cost of new carbon fiber, especially for non-aerospace applications where the demands for performance and certification by the FAA and the Department of Defense are lower. These efforts will result in fibers that cost about $5 per pound. This is the goal. The price for recycled fiber is about $8 per pound in the highest-value applications.

Most resins cost about $3 to $8 per pound and certainly have enough value to warrant recovery. Fiberglass costs about $2 per pound and is at the edge of being valuable enough to pay for the cost of recycling. These costs and a history of costs for new carbon fiber, the costliest part of a composite, are shown in Figure 110.

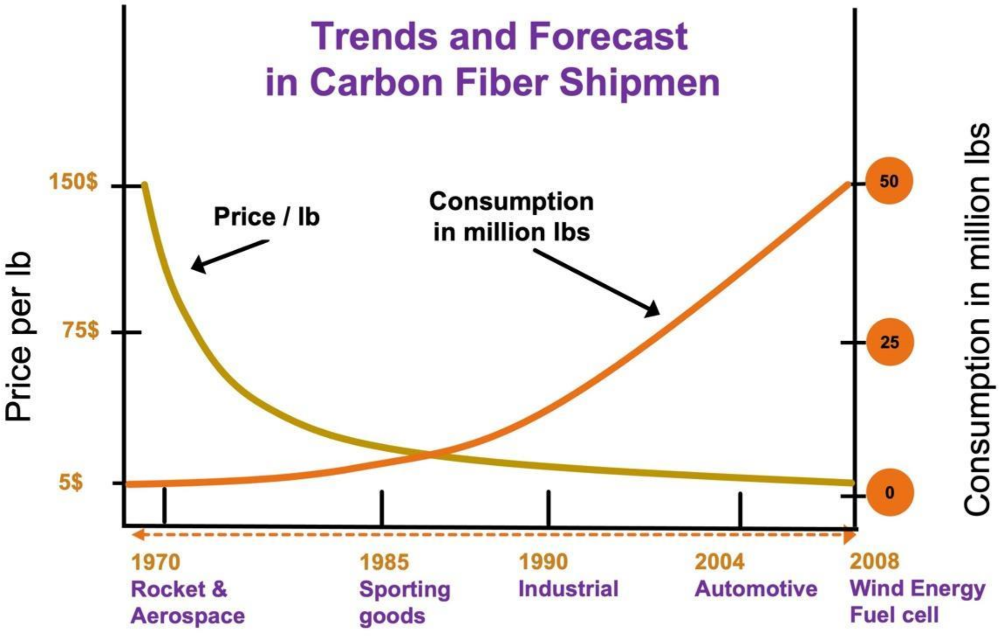


Figure 110 Carbon fiber price and consumption over time

The best method, at the present time, to recover both fibers and thermoset resins is solvolysis. In this process a solvent is used to dissolve the resin and free the fibers. Generally, the fibers retain nearly 100% of their original properties when they are tested after the resin is removed. The resin can be recovered from the solvent by some standard chemical process like precipitation, distillation, etc. The resin properties after separation from the solvent are about 80% of the originals. The minor decrease in properties for the resin are because the solvolysis process may require substantial heating to break the bonds of the thermoset resin. When polymers are heated, especially thermosets, some minor degradation is common. The solvent can usually be reused so waste solvent is not a problem.

To reduce the amount of heating and to speed up the solvation of the resins, catalysts are sometimes used. A catalyst is a chemical that will accelerate a chemical reaction but does not get used up in the reaction itself, thus remaining in the solution to assist in other chemical reactions throughout the solution. Often catalysts are metals, like platinum, that provide preferred sites for reactions to occur. When the reaction has occurred, the molecules leave the site and the platinum remains behind. A platinum catalyst is used in many automobiles to help change exhaust gases to other gases that are not harmful or polluting.

Several companies are very active in solvolysis and most consider their process very proprietary and keep the details secret. However, the results of several of these processes are quite favorable. Typical products used for the recovered fibers and resin are non-aerospace structural uses such as skis, snowboards, tubes for liquid transport, and face sheets for luggage storage bins on airplanes.

Thermoplastic composites can be recycled by melting the resin (or, if preferred) using the solvolysis techniques described above. When melted, the thermoplastic resin can be removed from the fibers and cooled. It will retain nearly 100% property levels. The fibers will also retain nearly 100% property levels.

Recover Fibers Only

The most common method for recovering the fibers only is by pyrolysis. This is a process where the composite is heated in an inert atmosphere, that is, an atmosphere where there is no oxygen. (Normally the reaction vessel is filled with nitrogen gas.) Because the decomposition temperatures for most matrix materials are below the melting points of the fibers (both carbon and glass), the temperature of the reaction vessel can be above the decomposition temperature of the resin without affecting the fibers.

During pyrolysis, the resin is decomposed and converted into various gases whose composition depends on the type of resin and the temperatures of pyrolysis. Normally the gases would be simple gases like carbon monoxide, methane, ethane, and propane. These gases can be collected and sold for use in various chemical and thermal processes. Some of them might even be used to make new polymers. Others might be burned (methane, propane) to help create heat used in the pyrolysis operation.

The fiber properties after pyrolysis are usually about 80% of the original properties. This is somewhat lower than solvolysis but the pyrolysis process is somewhat less expensive than solvolysis because it is faster and simpler.

Because the fibers have properties that are close to original, several semi-structural applications have been demonstrated for the post-pyrolysis fibers. One of the principal applications is cases for laptop computers. In this application the light weight, strength, and stiffness of the carbon fibers are very valuable. A photo of a laptop with a composite case is shown in the following figure.

Figure 111 Laptop with recycled carbon fiber case

Recycle by Chopping and Remolding

After the composite is cured, it can no longer be reshaped unless the matrix is a thermoplastic and then the reshaping requires melting the matrix. Therefore, a method for remolding cured composites is to chop the composite into pieces about the size of a coin and add resin so that the chopped pieces flow with the resin when put under pressure in a compression mold. The viscosity of the mixture must be thick enough to move all the materials to the edges of the mold during compression, but not so thick that the solid pieces sit in the center of the mold and don't move at all. (This is what would happen if no resin were added to the chopped composites.)

If the material to be recycled is uncured prepreg, it is best to remove the non-stick paper backing and then freeze the material before it is chopped.

The costs of chopping the cured and prepreg composites are low, thus resulting in this process as one of the least expensive composite recycling methods. However, chopping will significantly reduce the strength of the composite fibers. Therefore, applications should be non-structural or semi-structural and would allow the parts to not be optimized for weight savings. A typical application for this method is use in park benches. In this and similar applications, adding weight to compensate for a loss in strength of the fibers is not a problem. A typical park bench is shown in the following figure.

This general process of chopping, adding additional resin, and remolding is used to make rebond polyurethane that is widely used as a pad under carpets. The scrap polyurethane foam is chopped and put into a mold along with additional polyurethane liquid. The mold is closed and the mixture is heated to cure. The solid block of material is removed from the mold and sliced to create the carpet pad. Hence recycling by chopping and molding is a well-known process and should be helpful in making the composite parts.

Figure 112 Molded park bench

Recycle by Direct Remolding

This method only works with uncured prepreg material where the resin can still be molded. In this method the prepreg pieces are put into the mold after removing the paper backing. There can be some effort to spread the pieces around so that the entire mold is covered with prepreg uniformly (without too much effort) and the entire mold surface is covered. The mold is then closed and the prepreg is compressed and molded into a new shape. Because the resin on the prepreg is still moldable, there is no need to add additional resin, although that can be done if desired, thus ensuring the prepreg pieces are well bonded together.

Normally the parts made by this process do not have tight dimensional requirements. That is, the thickness over a single part and from one part to another could vary. Many products fit into these criteria. One, in particular, is sound barriers at airports that need to be moved. These take advantage of the good strength and light weight of the composite but do not need to be the same thickness. Other dimensions are controlled by the molding operation. An example of this type of sound barrier is shown in the figure below.

Figure 113 Sound barrier for airports

Avoid Landfill by Any Method

Although not of high value, composites can be chopped and then combined with other materials as a filler. In some cases, the composite will add strength or stiffness, but it might just add volume to the mix. Some examples of this “last resort” method are:

- Combining with plastics as a filler for artificial wood for decks, bench seats, walkways, piers, and other places where wood rotting and excessive needs for painting are a problem.
- Combining with asphalt to enhance driveways, running tracks, bridge decks, and other areas where the greater flexibility of composites versus rocks can be a benefit.
- Combine with sawdust and a resin binder to make planks that can be used for manufactured furniture, shelving, and other MDF (medium density fiberboard) applications.

Biodegrading as a Recycling Method

Many people believe that products that disappear through biodegradation are the best answer for the environment. While eliminating litter is certainly improved through biodegradation, the process of biodegradation has some negative aspects that are seldom understood. To see the full effect of biodegradation, we must understand where energy is stored by nature.

Most of our energy comes, ultimately, from the sun. Oil and coal are from plants that used solar energy to grow, the winds are caused by solar heating, dams hold water that has evaporated and condensed as rain or snow and then flows toward the oceans, and solar-powered installations make electricity directly or indirectly from the sun. The only non-solar sources of energy I can think of right now are nuclear, geothermal, hydrogen gas, and chemical (batteries).

Because solar power is very difficult to store for long periods, the best long-term energy storage mechanism we have is within chemical bonds and the most abundant and easiest to use source of that bond energy is in polymers. These long chain molecules can be natural or synthetic. The natural polymers include wood, oil, coal, plants, and many animal parts. The most common synthetic polymers are plastics and composites. The energy stored in the bonds of natural polymers and of synthetic polymers is essentially the same. But natural polymers degrade much more rapidly than synthetic polymers when exposed to air, micro-organisms, and sunlight. Therefore, natural polymers do not have the long-term energy storage capability that plastics and composites have.

It is true that the natural polymers disappear more quickly and, therefore, do not stay around as litter or stay in landfills, but at what cost? When any polymer degrades, the energy stored in the bonds is released, usually as heat. That is why we can create heat by burning oil or coal or wood. We are simply accelerating the degradation by increasing the heat. When any polymer degrades, either in the landfill or along the roadside, it will also release heat and that heat has an effect in global warming because the heat goes directly into the air. Each degraded polymer releases a small amount of heat and so we don’t notice it, but when all the biodegradable polymers and decaying plants and degrading other natural polymers are considered, the amount of heat is staggering. Therefore, plastics and composites are like reservoirs of energy that we can keep for the future when oil, coal, or other sources of energy are gone or difficult to obtain. Remember also that when natural polymers degrade, they often degrade to harmful materials that can be washed into ground water. This is a potential source of water contamination.

Another valuable reason to store polymers for future needs is to obtain the chemicals that are present or can be made from polymers. Most medicines, medical devices, plastics, composites, and millions of other useful materials are made, ultimately, from the chemicals obtained from oil, coal, or other polymer materials that nature has kept for us. Synthetic polymers are simply reusing these chemicals and are, themselves, storing the energy for future use.

Fun Activity

Objective: Recycle a composite part

Procedure:

1. Find or make a composite part that you can recycle
2. Choose a recycling method.
3. Design a set of steps to follow in doing the recycling. (A recycling procedure.)
4. Follow the steps.
5. After the recycling is complete, examine the fibers (dry) with a magnifying glass or a microscope to determine the extent of resin removal.

Chapter 8 — Planning your Future

As Yogi Berra, a hall of fame catcher with the New York Yankees, said, “Predictions are hard, especially when they are about the future.” Yogi’s statement is especially true in a time, like now, when change is no longer slow or evolutionary. Change today is episodic and random. These times defy predictions and make planning your future very difficult.

How can you plan for the future at a time when change occurs so quickly? Planning may seem futile because our current view of the future is likely to be different from the real future when it arrives. In a strange, almost magical way, the person who can plan properly in these times will achieve greater success and have a better chance of life-long happiness. Some well-spent time and careful thought, plus use of proven techniques for planning, will greatly improve your ability to plan in the midst of chaotic times. Here are some ideas that will, hopefully, help you make decisions and plan for the future.

There are three types of decisions that are required in life and in your career. Understanding these will help you plan. The first type are decisions about immediate living, the second are decisions about the structure of your life, and the third are strategic decisions about the future. Each type of decision will be discussed below.

Immediate Living Decisions

These are the decisions that run your day. They are simply decisions required to get done what you need to do. These decisions are day-to-day (maybe hour-to-hour). They include deciding when to get up, what to wear, what to eat, what work to do, what classes to attend, what activities to do after school or work, what time to go to bed, etc. These decisions are usually easy to make and the consequences of making a poor decision have only minor consequences. These Immediate Living Decisions are straightforward, frequent, and self-forcing (that is, they must be made to continue your daily life). In the business world these are called operational decisions because they are required to keep the business going.

Structure of Life Decisions

The Structure of Life Decisions are less frequent than Immediate Living Decisions but the structural decisions provide guidance for the immediate decisions. Typical structural decisions include those affecting your family, home, choice of school, and might even include decisions about the type of company you will work for. These decisions are made monthly, annually, or when changes occur in your life, that is, when you are forced to depart from your regular routine. Therefore, Structure of Life Decisions are best made before becoming self-forcing so that proper thought and evaluation can be done. In the business world these are decisions about organizational structure, reporting procedures, and hiring.

The purposes of structural decisions are related to developing efficient and productive use of your talents and establishing a way of life. They are about the structure of your life. These decisions can require considerable thought and often are made in cooperation with others who are close to you. These decisions could include the university you might attend, the place where you will live, the car that you will buy, etc. These can be changed but often with some moderate difficulty.

Strategic Decisions

These decisions are about your fundamental philosophy of life and values. They are related to your underlying principles. Strategic decisions are made infrequently, are extremely complex, have severe consequences, and are not self-forcing. Strategic Decisions are about the future.

Strategic Decisions do not typically come up in the normal living of life but once made, the Strategic Decisions direct both Immediate Living Decisions and Structure of Life Decisions. Many Strategic Decisions are formed during your childhood and teenage years. As you become an adult these decisions are refined and, sometimes, altered significantly as you enter the wider world. If you have a major change in your life, especially a tragic or serious mistake, that is a time to give long and careful thought to the strategy of your life.

To help in making these Strategic Decisions, two questions have proven to be useful.

1. What do you want to be (perhaps asking yourself, What do I want to be in 10 years)?
2. How should you get to this desired position?

These questions focus on how you should change. Thinking about the nature of change, you will realize that change requires a different way of thinking when compared to the thinking done for Immediate Life Decisions and Structure of Life Decisions. Strategic Decisions require establishing a way of thinking (sometimes called a paradigm) that governs how you think about life. After the decision is made, it requires constant reinforcement and that is how the Immediate and Structural Decisions cooperate with the Strategic Decision. In other words, your actions must be aligned with your Strategic Decisions.

Choosing a Career or Job or Company

Four factors are critical in deciding what career you should pursue or what company or job you should accept. These factors concern you personally. They are the following:

- Skills (that is, what do you have in your toolbox from school and life),
- Abilities (what innate strengths do you have),

- Values (what is important to you), and
- Interests (what do you do when you aren’t working).

You might want to make a written list of each of these factors because often writing will help you focus better.

After careful consideration of each factor, put them together in a Venn Diagram (see Figure 114) where you list each of the factors in a circle and overlap the circles. Consider what overlaps there are between each pair of factors. And then, seek to find careers or jobs that might overlap with all the factors. Write down a diagram for each possible career choice and identify where it fits. Hopefully, one or more will lie in the convergence area and be a perfect career choice.

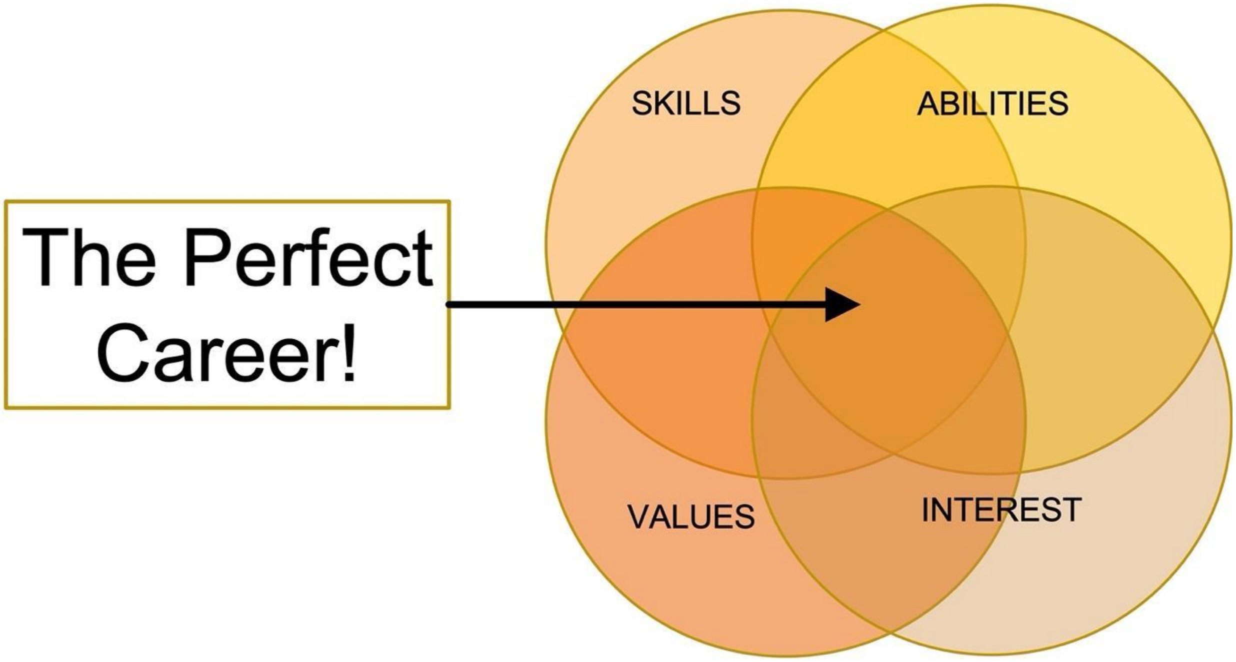


Figure 114 Venn Diagram on career choice methods

Relating Decision-Making to Composites

This book is about understanding composites and helping you to make a career decision. If you have gained an interest in composites from the book, further investigation is a good idea. You might contact SAMPE, a professional society focusing on composites, and ask them to refer you to someone who is in the composites field. You might ask about schools, either universities or technical colleges, where composites are taught or visit a company where composites are molded. I give you my best wishes in making the future what you want.

Acknowledgements

After writing the first draft of this book, I wanted to get opinions from experts in the field of composites to ensure that what I had said was technically accurate. I therefore sent the draft to Les Cohen and Ted Lynch, two of the best experts I know. They have different areas of specialization but both have been involved with composites for many years and I trust their judgement. Thanks to them for reading the draft and suggesting edits to improve it. They also helped choose the design for the cover of this book.

Les and Ted are both on the board of the SAMPE Foundation, the charitable arm of SAMPE (a professional society). The Foundation focuses on improving education, especially in grades K to 12 and they felt that a book on composites would both encourage students to become interested in STEM education and also consider entering the field of composites. The SAMPE Foundation paid for the writing and publishing of this book. Many thanks.

I wanted the opinion of a person who has just finished high school and so I sent a copy of the draft to Stockton Haws, a man who I have recently met. What a fine person he is and he readily agreed to read the book from a student perspective. He made many very helpful suggestions. Thank you, Stockton.

Finally, I discussed many analogies, examples, and other details with my wife of over 58 years, Margaret. She is non-technical but, having lived around me for so long, she has a good feeling for technical jargon, but can help me explain concepts so that they are easier to understand. She has been a great help and has edited the entire book.

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