Chapter 4

General Assessment of Fiber-Reinforced Composites Selection in Wind Turbine Blades

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I. INTRODUCTION

The reduction of fossil fuel dependency is an important goal for both developed and developing countries. All these energy sources are limited and at the same time these energy sources create pollution problems. This has led to the focus on a sustainable energy supply, which implies optimized use of energy, minimized pollution. To achieve this goal, the renewable energy production in particular world energy generation must be drastically increased.

That is why wind energy is prominent and it is one of the solutions to the global energy problem. The wind energy is generated by using wind turbines. Wind speed is considered to be increased with the help of continuity principle [1]. This can be realized by installation and expansion of many off-shore and on-shore wind parks built with large and extra-large wind turbines.

Wind turbines come in many sizes and configurations and are built from wide range of materials. In simple terms, a wind turbine consists of a rotor that has wing shaped blades attached to a hub; a nacelle that houses a drivetrain consisting of a gearbox, connecting shafts, support bearings, the generator, plus other machinery; a tower; and ground-mounted electrical equipment [2].

The turbine blades play very important role in the wind turbines. Blades are required to preserve an optimum cross-section for aerodynamic efficiency to generate the maximum torque to drive the generators. The efficiency of the wind turbine depends on the material of the blade, shape of the blade and angle of the blade. Therefore, the material of the turbine blade plays a vital role in the wind turbines. The material of the blade should possess high stiffness, low density and long fatigue life features (Fig. 1) [3].

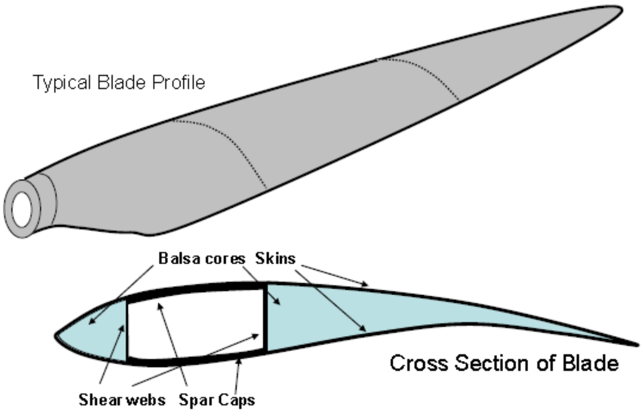


Fig. 1 Typical Blade profile and its cross-section [3]

The wing shaped blades on the rotor actually harvest the energy in the wind stream. The rotor converts the kinetic energy in the wind to rotational energy transmitted through the drivetrain to the generator. Generated electricity can be connected directly to the load or feed to the utility grid [4].

The weight and cost of the turbine are the key points for making wind energy competitive with other power sources, because research programs have significantly improved the efficiency of the rotor and maximized the energy capture of the machine. The real opportunity today is through better, low cost materials and though high volume production, while ensuring the reliability is maintained [2].

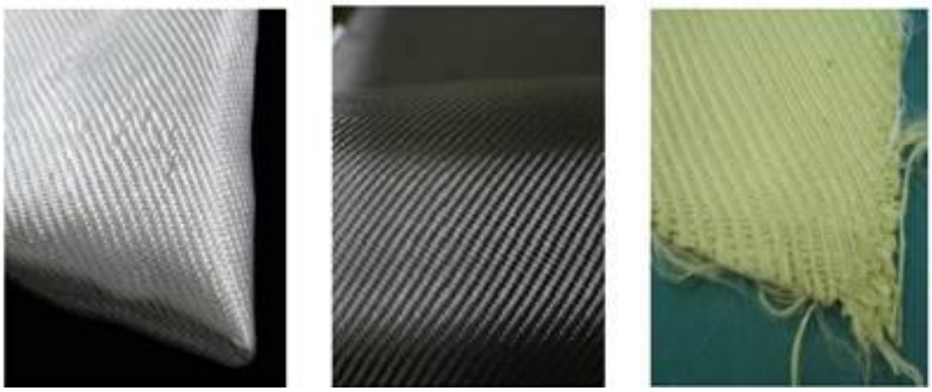
The components of turbines are changing as the technology improves and evolves. There is a trend toward lighter weight systems. Light weight, low cost materials are especially important in blades and towers for several reasons. First, the weight of the blades and rotor is multiplied throughout the machine. The tower weight is a key feature because it is typically 60% of the weight of the turbine above the foundation, due to the fact that sophisticated lightweight, high-strength materials are often too costly to justify their use.

A wide range of materials are used in wind turbines. There are substantial differences between small and large machines and there are projected changes in designs that will accommodate the introduction of new material technologies and manufacturing methods. Components and materials for wind turbines are major and expanding business opportunities for at least the next 10 years.

There are new component developments underway now that will significantly change the materials usage patterns. Generally there are trends toward lighter weight materials, as long as the life-cycle cost is low.

Most composites are made up of just two materials. One material (the matrix or binder) binds together a cluster of fibers or the fragments of a much stronger material and the second material (the reinforcement) surrounds these fibers or fragment. Nowadays, many wind turbine manufacturers are taking a big interest in composite materials which many researcher of wind technology see as the materials of the future. The main concern is to get the cost down, so that composites can be used in products and applications which at the present time do not justify the cost. At the same time they want to improve the performance of the composite, such as making them more resistant to impact [5].

Mechanical and physical properties of fibrous composite materials are beneficial compared to other constructional materials of wind turbine blades. The major advantages of this type of materials are low weight and high strength [6, 7]. Therefore, wind turbine blades built up with composite materials have much less weight than traditional constructions. Composite materials reinforced with fiberglass (Fig. 2a), carbon (Fig. 2b) and Kevlar (Fig. 2c) fibers are considered [8].



(a) (b) (c)

Fig. 2 Composite materials: (a) Fiberglass, (b) Carbon, (c) Kevlar [8]

Most rotor blades in use today are built from glass fiber-reinforced-plastic (GRP). Other materials that have been tried include steel, various composites and carbon filament-reinforced-plastic (CFRP). As the rotor size increases on larger machines, the trend will be toward high strength, fatigue resistant materials. As the turbine designs continually evolve, composites involving steel, GRP, CFRP and possibly other materials will likely come into use. For purposes of example, Gurit blades materials portfolio is shown in Fig. 3 [9].

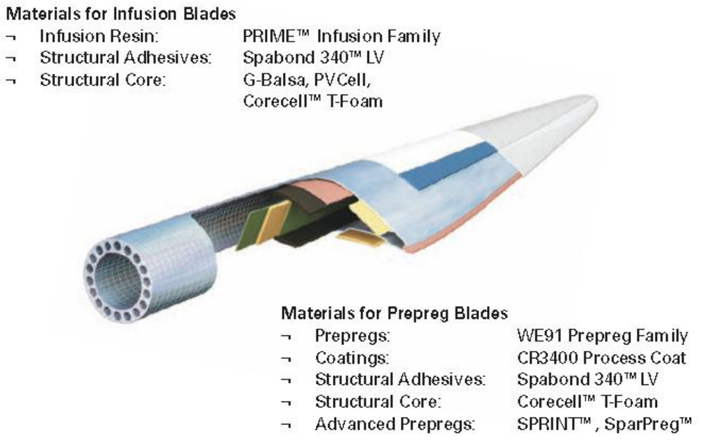


Fig. 3 Gurit blades material portfolio [9]

Blades are primarily made of GRP, which is expected to continue, while use of CFRP may help to reduce weight and cost to some extent. Low cost and reliability are the primary drivers for material selection. Increasing the use of offshore applications may partially offset this trend in favor of the use of composites. New trend of advanced composites used in wind turbines blades should be developed, improved and utilized.

In the longer term, there is scope for improving the materials used in wind turbine blades. As indicated previously, wind turbine blades need to be strong, stiff and light. Two particular weaknesses of laminated fiber-reinforced composites are their low tensile and shear strength in the out-of-plane direction and the fact that developments that increase their stiffness and tensile strength in the fiber direction do not generally provide the same beneficial effect on the compressive strength. A further consideration is recyclability. The thermosetting resins currently used cannot be recycled, and the only disposal method for fiber-reinforced composites containing these resins is to break the composite up into small pieces and incinerate them, feeding the heat into a district heating system. This is not necessarily a major disadvantage, but to allow greater flexibility in recycling and disposal is desirable. Carbon fiber reinforcements are being introduced into blades. These can be used to improve the stiffness and tensile strength in the fiber direction, as compared to materials containing glass, but the gains in compressive strength are generally significantly lower [10].

Thus, it is often most economical to use a mixture of glass and carbon, with carbon being used mainly to increase the global blade stiffness. The same is likely to apply to any new high-strength and high-stiffness reinforcement fibers that may be introduced. At present, moderately priced polymer resins and adhesives tend to be either strong, stiff, and brittle or weak, compliant, and tough. The development of products that provide a better combination of strength (including good adhesion), stiffness and toughness than those available at present would be a great step forward. However, such materials must not degrade in service and should, if possible, be recyclable [10].

In this chapter, the application of advanced composites in wind turbine blades technology, requirements for such composites, their properties and constituent, manufacturing technologies and defects are reviewed.

II. COMMONLY USED MATERIALS IN WIND BLADES

Nowadays, modern wind turbine engineers avoid building large machines with an even number of rotor blades. The most important reason is the stability of the turbine. A rotor with an odd number of rotor blades (and at least three blades) can be considered to be similar to a disc when calculating the dynamic properties of the machine. A rotor with an even number of blades will give stability problems for a machine with a stiff structure. The reason is that at the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lower most blade passes into the wind shade in front of the tower.

So, most of the modern wind turbines are three-bladed designs with the rotor position maintained upwind (on the windy side of the tower) using electrical motors in their yaw mechanism. The design life time of modern wind turbines is normally thought to be 20 years. The basic design aspects for a rotor blade are the selection of material and shape. The material should be stiff, strong and light [11].

The development of wind turbines has made a significant contribution to human achievement and technological advancement throughout history. Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective and reliable. The material selection of the wind turbine blades plays an important role in the wind turbine designs. An ever-increasing variety of materials is available today, with each having its own characteristics, applications, advantages and limitations. When selecting materials for engineering designs, we must have a clear understanding of the functional requirements for each individual component. In selecting materials for an application, technological considerations of material properties and characteristics are important. The economic aspects of material selection, such as availability, cost of raw materials and cost of manufacturing, are equally important [11, 12].

There are number of factors which effect the material selection. They are properties of materials, performance requirements, material’s reliability, safety, physical attributes, environmental conditions, availability, disposability and recyclability, and finally economic factors [12]. In these properties,

- One of the most important factors affecting selection of materials for engineering design is the properties of the materials. The important properties of the materials are mechanical, thermal, chemical properties, etc.
- The material of which a part is composed must be capable of performing a part’s function (always it must be possible or not) without failure.
- A material in a given application must also be reliable.
- A material must safely perform its function.
- Physical attributes such as configuration, size, weight, and appearance sometimes also serve functional requirements can be used.
- The environment in which a product operates strongly influences service performance.

- A material must be readily available, and available in large enough quantity, for the intended application.
- The cost of the materials and the cost of processing the materials into the product or part. The development and manufacture of satisfactory products at minimum cost is to make a sound, economic choice of materials [11, 12].

The material selection process involves the following major operations:

- Analysis of the materials application problem.
- Translation of the materials application requirements to materials property values.
- Selection of candidate materials.
- Evaluation of the candidate materials.

In any material selection, the following requirements should be focused; they are:

- High material stiffness is needed to maintain optimal shape of performance.
- Low density is needed to reduce gravity forces.
- Long-fatigue life is needed to reduce material degradation [11, 13].

The optimal design of the rotor blades is today a complex and multifaceted task and requires optimization of properties, performance and economy [11]. The exact shape of the internal structure will determine the stiffness and strength of the blade under each loading mode for any given materials (Fig. 4) [3]. In general terms, however, we need a material that is as light as possible for a given stiffness in order to satisfy the blade design criteria and to minimize the weight induced fatigue loads [14, 15].

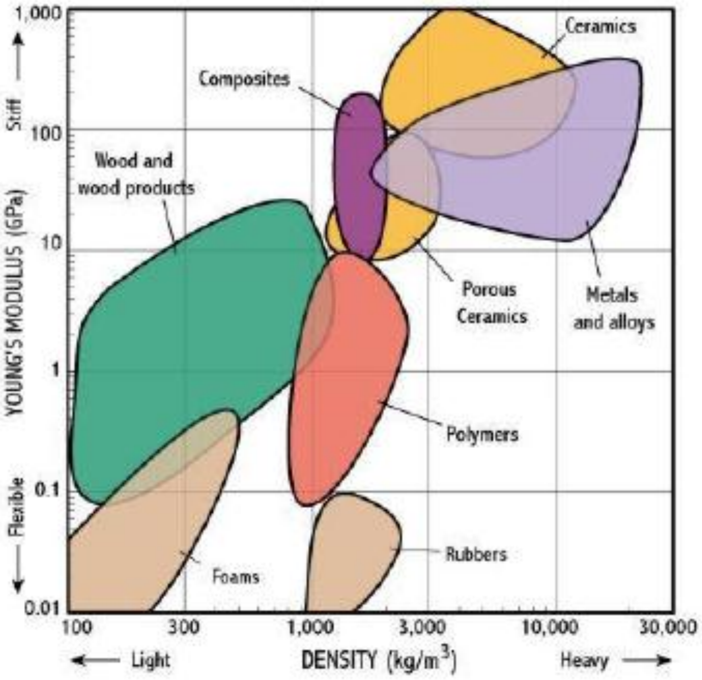


Fig. 4 Ashby material selection diagram [3], [15], [24]

Wind energy is harvested by the rotation of the wind turbine's rotor blades. Rotor blades have historically been made of wood; but because of its sensitivity to moisture and processing costs, modern materials such as glass fiber-reinforced-plastic (GFRP), carbon fiber-reinforced-plastic (CFRP), steel and aluminium are replacing the traditional wooden units.

During the 19th century blades used to be made by wood and canvas. Wood shows good fatigue characteristics and it is relatively cheap; therefore, could be used for small wind turbine applications. However, wood is not strong enough for larger wind turbines. To improve its resistance against environmental degradation, wood was coated with weather resistance finish [16].

Wood is a composite of cellulose and lignin; it finds many engineering applications and has long been a common construction material. Woods are potentially interesting because of their low density, but their rather low stiffness makes them difficult to limit the (elastic) deflections for very large rotor blades. Even wood materials with cellulosic fibers, all aligned in the major load-bearing directions, are close to the maximum performance possible for wood. Furthermore, wood is a natural material and thus environmentally attractive, but at the same time difficult to obtain in reproducible and high quality, which is a requirement for stable and economical manufacturing of rotor blades and thus economically attractive wind energy.

In the late 19th century, wood was replaced with thin sheets of galvanized steel and it became thoroughly popular. This initiated extensive research and understanding of metal behaviour for wind turbine applications. Alloy steel was once thought to be an optimum choice for blade fabrication, but was soon abandoned because of its high weight and low fatigue level. However, steel brought a range of problems like excessive weight, therefore, aluminium was introduced but it also faced problems like low fatigue resistance and high cost.

Then the most popular and widely used material for wind turbine blades was introduced called composites, more specifically polymer matrix composite (PMC) also called as fiber reinforced plastic (FRP). These composites were composed of 2 parts; matrix and fiber. These two combined parts form a useful material for blade application. The most commonly used fiber and its matrix is E-glass fiber and polyester resin for structural applications. A fiber is the primary load carrying element of the composite material. Its orientation in alternating directions gives the material strength and stiffness. The composite material is only strong and stiff in the direction of the fibers. Unidirectional composites have predominant mechanical properties in one direction and are said to be anisotropic, having mechanical and/or physical properties that vary with direction relative to natural reference axes inherent in the material. The amount of fiber (FVF- Fiber volume fraction) in the resin determines the strength of the composites. The volume fraction of fiber is highly dependent on the manufacturing method. However, fiber can only be added up to a certain extent, after which composite’s mechanical properties begin to deteriorate. The reason behind is related with the lack of resin to transfer the exerted load to reinforced fibers. Normal hand layup technique achieves FVF of around 30-35%, while sophisticated techniques like SCRIMP and vacuum infusion using prepregs can achieve up to 70%. The manufacturing technique also determines the extent of air inclusion and voids which reduce strength directly [17, 3, 12, 18].

Composite materials are becoming more important in the construction of wind turbine blade structures. New generation of large wind turbine blades are designed with all composite fuselage and wing structures, and the repair of these advanced composite materials requires an in-depth knowledge of composite structures, materials and tooling. These materials have a significant part to play in maintaining and developing the wind turbine industry.

Composites are classified according to their matrix phase. There are polymer matrix composites (PMCs), ceramic matrix composites (CMCs) and metal matrix composites (MMCs). Materials within these categories are often called "advanced" if they combine the properties of high strength and high stiffness, low weight, corrosion resistance, and in some cases special electrical properties. This combination of properties makes advanced composites very attractive for aircraft, aerospace structural parts and wind turbine blades [17].

The primary advantages of composite materials are their high strength, relatively low weight and corrosion resistance. It was recognized that structures are hybrids of different engineering materials and that to achieve true benefits from advanced composites, developments in this area must include the integrated structural system as well. It is important to create critical mass for this technology if it is to be successful in a commercial exploitation.

A matrix supports the fibers and bonds them together in the composite material. The matrix transfers any applied loads to the fibers, keeps the fibers in their position and chosen orientation, gives the composite environmental resistance and determines the maximum service temperature of a composite.

III. MECHANICAL PROPERTIES OF ADVANCED COMPOSITES

If composites combine the properties of high strength values and high stiffness values, with low weight and corrosion resistance, these materials are often called as advanced composite materials (ACMs). Advanced composite materials are also known as advanced polymer matrix composites [19]. These are generally characterized or determined by unusually high strength fibers with unusually high stiffness, or modulus of elasticity characteristics, compared to other materials, while bound together by weaker matrices (Fig. 5). These are termed advanced composite materials (ACM) in comparison to the composite materials commonly in use such as reinforced concrete, or even concrete itself. The high strength fibers are also low density while occupying a large fraction of the volume [20].

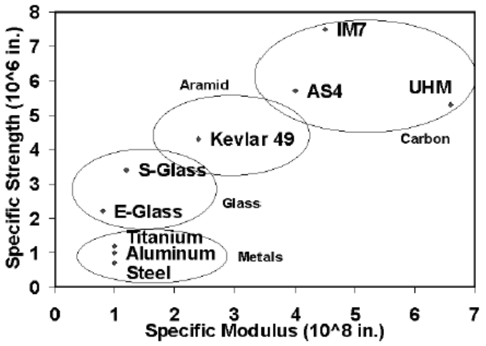


Fig. 5 Advanced composites general characteristics [20]

Structural properties, such as stiffness, dimensional stability and strength of a composite laminate, depend on the stacking sequence of the plies. The stacking sequence describes the distribution of ply orientations through the laminate thickness. As the number of plies with chosen orientations increases, more stacking sequences are possible. For example, a symmetric eight-ply laminate with four different ply orientations has 24 different stacking sequences. The strength and stiffness of a composite build-up depends on the orientation sequence of the plies. The practical range of strength and stiffness of carbon fiber extends from values as low as those provided by fiberglass to as high as those provided by titanium [18]. Advanced composites can be classified according to their fiber orientation and the used types of fiber and resin [19]. These classifications are detailed in the following sub sections.

A. *Fiber Orientation*

This range of values is determined by the orientation of the plies to the applied load. Proper selection of ply orientation in advanced composite materials is necessary to provide a structurally efficient design. The part might require 0° plies to react to axial loads, ±45° plies to react to shear loads and 90° plies to react to side loads. Because the strength design requirements are a function of the applied load direction, ply orientation and ply sequence have to be correct. It is critical during a repair to replace each damaged ply with a ply of the same material and ply orientation. The fibers in a unidirectional material run in one direction and the strength and stiffness is only in the direction of the fiber. Pre-impregnated (prepreg) tape is an example of a unidirectional ply orientation. The fibers in a bidirectional material run in two directions, typically 90° apart. A plain weave fabric is an example of a bidirectional ply orientation. These ply orientations have strength in both directions but not necessarily the same strength (Fig. 6) [18].

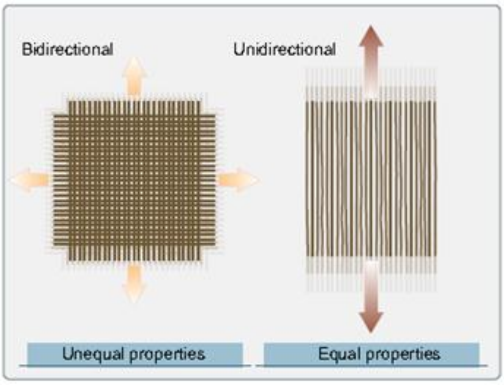


Fig. 6 Bidirectional and undirectional material properties [18]

The plies of a quasi-isotropic layup are stacked in a 0°, –45°, 45° and 90° sequence or in a 0°, –60° and 60° sequence. (Fig. 7) These types of ply orientation simulate the properties of an isotropic material. Many wind turbine blades composite structures are made of quasi-isotropic materials.

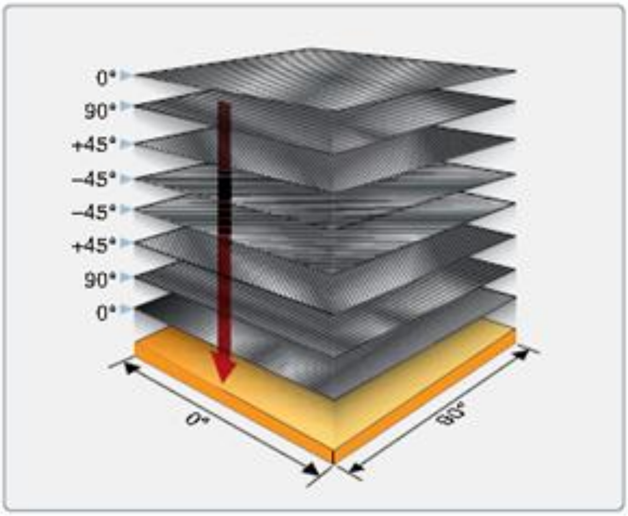


Fig. 7 Quasi-isotropic material lay-up [18]

Warp indicates the longitudinal fibers of a fabric. The warp is the high strength direction due to the straightness of the fibers. A warp clock is used to describe direction of fibers on a diagram, spec sheet, or manufacturer’s sheets. If the warp clock is not available on the fabric, the orientation is defaulted to zero as the fabric comes off the roll. Therefore, 90° to zero is the width of the fabric across (Fig. 8).

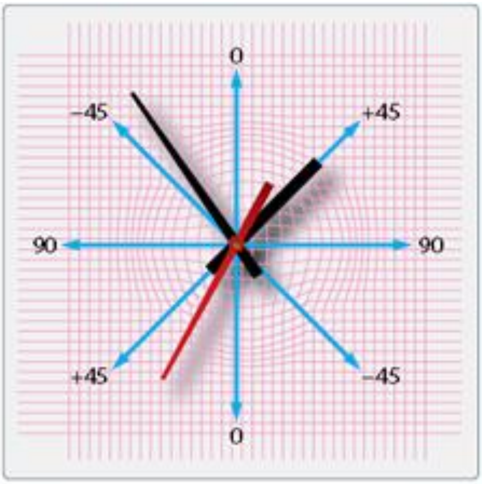


Fig. 8 A warp clock [18]

All product forms generally begin with spooled unidirectional raw fibers packaged as continuous strands. An individual fiber is called a filament. The word strand is also used to identify an individual glass fiber. Bundles of filaments are identified as tows, yarns, or rovings. Fiberglass yarns are twisted, while Kevlar® yarns are not. Tows and rovings do not have any twist. Most fibers are available as dry fiber that needs to be impregnated (impreg) with a resin before use or prepreg materials where the resin is already applied to the fiber [18].

A roving is a single grouping of filament or fiber ends, such as 20-end or 60-end glass rovings. All filaments are in the same direction and they are not twisted. Carbon rovings are usually identified as 3K, 6K, or 12K rovings, where K refers to 1,000 filaments. Most applications for roving products utilize mandrels for filament winding and then resin cure to final configuration. Unidirectional prepreg tapes have been the standard within the wind turbine blades industry for many years, and the fiber is typically impregnated with thermosetting resins. The most common method of manufacture is to draw collimated raw (dry) strands into the impregnation machine where hot melted resins are combined with the strands using heat and pressure. Tape products have high strength in the fiber direction and virtually no strength across the fibers. The fibers are held in place by the resin. Tapes have a higher strength than woven fabrics (Fig. 9) [18].

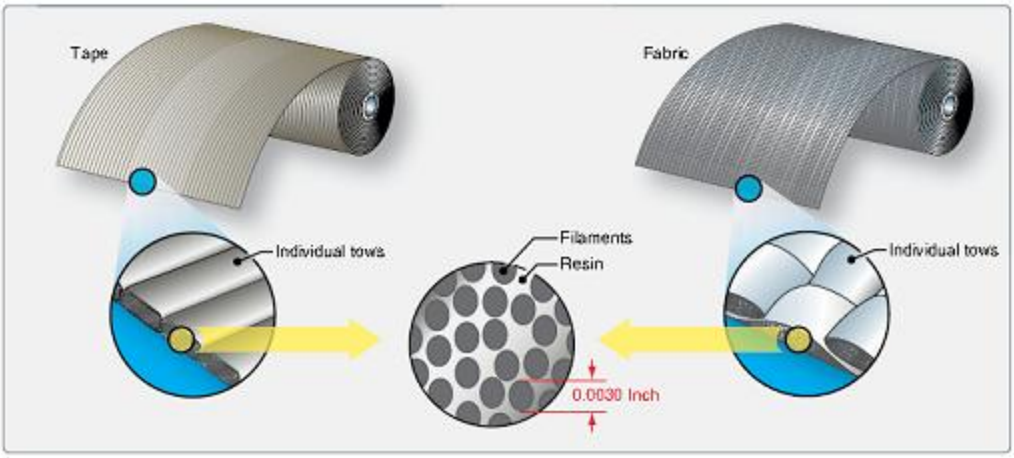


Fig. 9 Tape and fabric products [18]

Most fabric constructions offer more flexibility for layup of complex shapes than straight unidirectional tapes offer. Fabrics offer the option for resin impregnation either by solution or the hot melt process. Generally, fabrics used for structural applications use like fibers or strands of the same weight or yield in both the warp (longitudinal) and fill (transverse) directions. For aerospace structures, tightly woven fabrics are usually the choice to save weight, minimizing resin void size and maintaining fiber orientation during the fabrication process. Woven structural fabrics are usually constructed with reinforcement tows, strands, or yarns interlocking upon themselves with over/under placement during the weaving process. The more common fabric styles are plain or satin weaves. The plain weave construction results from each fiber alternating over and then under each intersecting strand (tow, bundle, or yarn). With the common satin weaves, such as 5 harness or 8 harness, the fiber bundles traverse both in warp and fill directions changing over/under position less frequently. These satin weaves have less crimp and are easier to distort than a plain weave. With plain weave fabrics and most 5 or 8 harness woven fabrics, the fiber strand count is equal in both warp and fill directions. Example: 3K plain weave often has an additional designation, such as 12 x 12, meaning there are twelve tows per inch in each direction. This count designation can be varied to increase or decrease fabric weight or to accommodate different fibers of varying weight (Fig. 10) [18].

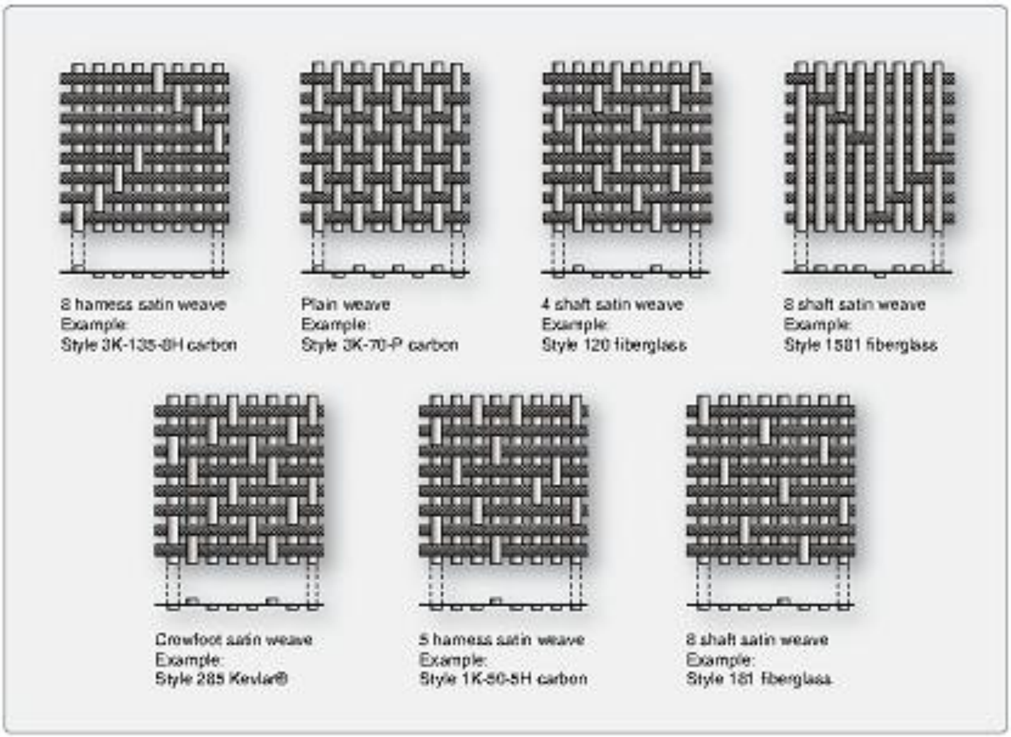


Fig. 10 Typical fabric weave styles [18]

Knitted or stitched fabrics can offer many of the mechanical advantages of unidirectional tapes. Fiber placement can be straight or unidirectional without the over/under turns of woven fabrics. The fibers are held in place by stitching with fine yarns or threads after preselected orientations of one or more layers of dry plies. These types of fabrics offer a wide range of multi-ply orientations. Although there may be some added weight penalties or loss of some ultimate reinforcement fiber properties, some gain of interlaminar shear and toughness properties may be realized. Some common stitching yarns are polyester, aramid or thermoplastics. (Fig. 11) [18].

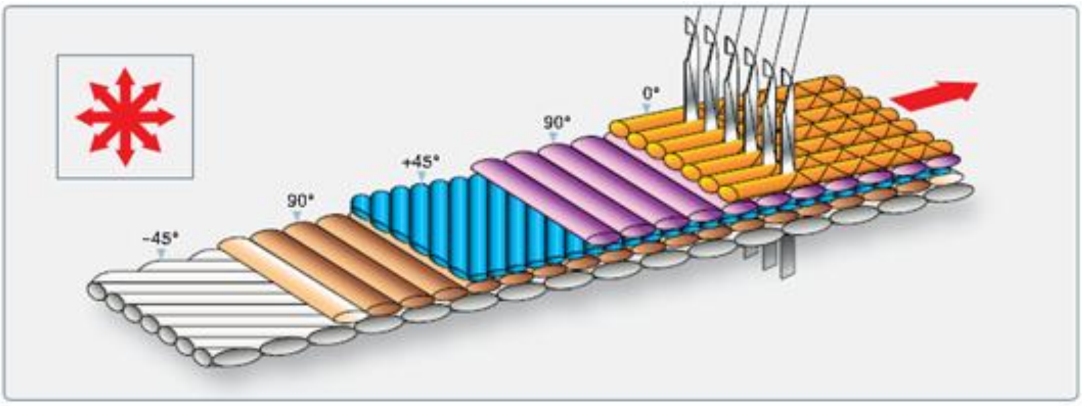


Fig. 11 Nonwoven material (stitched) [18]

B. *Types of Fiber*

Glass, carbon, boron or aramid fibers are the most common choices for advanced composite parts. The best fiber for a particular application depends on the required strength, stiffness, corrosion resistance and budget. Glass fiber is the most common reinforcing material used in polymer matrix composites. These have high tensile strength but low modulus compared with other fibers. Typical variants are:

- E-glass
- ECR-glass

- S-glass, R-glass and Te-glass
- Silica/quartz
- D-glass

The different types of glass are supplied in several different configurations, including:

- Fiberglass rovings
- Sheet moulding compound
- Woven rovings
- Chopped strand mat

Carbon fiber is the reinforcement material of choice for “advanced” composites, Carbon fiber exhibits excellent fatigue resistance which does not suffer from stress rupture compared with glass or aramid fibers. Carbon fibers are supplied in tows and may vary from 1000 fibers per tow to hundreds of thousands per tow. Untreated carbon fibers do not wet easily, so adhesion to the matrix must be achieved by mechanical interference coupled with surface treatment and chemical bonding between the fiber and the matrix. Typically they are defined as standard, intermediate and high modulus fibers. Carbon fiber properties are given in Table 1 [17].

Table 1 Carbon fiber properties [17]

	Standard modulus	Intermediate modulus	High modulus
Tensile Strength	3450-4830 MPa	3450-6200 MPa	3450-5520 MPa
Young's Modulus	220-241 GPa	290-297 GPa	345-448 GPa
Elongation at break	1.5-2.2%	1.3-2.0%	0.7-1.0%

Aramid fibers have the highest strength to weight ratio compared to other commercially available fibers. Kevlar manufactured by DuPont is a familiar brand name. Aramid fiber exhibits similar tensile strength to glass fiber, but can have modulus at least two times as great. Aramid is very tough allowing significant energy absorption but, compared to carbon, it is lower in compressive strength and has poorer adhesion to the matrix. It is also susceptible to moisture absorption. Aramid fiber properties depend on the structure used and can be tailored for high toughness or high modulus. Aramid (Kevlar) fiber properties are given in Table 2 [17].

Table 2 Aramid (Kevlar) fiber properties [17]

	Kevlar 29 High toughness	**Kevlar 49 High modulus**	**Kevlar 149 Ultrahigh modulus**
Tensile Strength	3.6 GPa	3.6-4.1 GPa	3.4 GPa
Young's Modulus	83 GPa	131 GPa	179 GPa
Elongation at break	4%	2.80%	2.0%

Boron fiber actually predates carbon fiber as a high-modulus reinforcement material. The cost of boron, however, has seen its demise, with its replacement with carbon fiber. They do not differ greatly from glass fiber in tensile strength, but can have modulus five times that of glass. Since the objective of reinforcement is to stiffen, this is a significant advantage. Their use is confined to niche markets, where the modulus advantage over carbon fiber is critical [17].

Fiber reinforcement materials are added to the resin system to provide strength to the finished part. The selection of reinforcement material is based on the properties desired in the finished product. These materials do not react with the resin but are an integral part of the advanced composite system. Potential worker exposure is typically higher in facilities that manufacture the fibers or use them to produce prepreg material. Most of the fibers in use are considered to be in the nonrespirable range. However, they do have the potential to cause eye, skin, and upper respiratory tract irritation as a result of the mechanical properties of the fibers [17].The three basic types of fiber reinforcement materials in use in the advanced composite industry are:

- carbon/graphite
- aramid
- glass fibers

Fibers used in advanced composite manufacture come in various forms, including:

- yarns
- rovings
- chopped strands
- woven fabric
- mats

Each of these has its own special application. When prepreg materials are used in parts manufacture, woven fabric or mats are required. In processes such as filament wet winding or pultrusion, yarns and rovings are used [12]. The most commonly used reinforcement materials are carbon/graphite fibers (the terms graphite and carbon are often used interchangeably). This is due to the fact that many of the desired performance characteristics require the use of carbon/graphite fibers. Currently, these fibers are produced from three types of materials known as precursor fibers:

- polyacrylonitrile (PAN)
- rayon
- petroleum pitch

The carbon/graphite fibers are produced by the controlled burning off of the oxygen, nitrogen and other noncarbon parts of the precursor fiber, leaving only carbon in the fiber. Following this burning off (or oxidizing) step, the fibers are run through a furnace to produce either carbon or graphite fibers. Carbon fibers are produced at furnace temperatures of 1 000-2 000 ℃, while graphite fibers require temperatures of 2 000-3 000 ℃. At these temperatures the carbon atoms in the fibers are rearranged to impart the required characteristics to the finished fiber. The PAN-based fiber is the more commonly used precursor in the advanced composite industry today [17]. Aramid fibers are another human-made product. These fibers are produced by manufacturing the basic polymer, then spinning it into either a paper-like configuration or into fiber. Aramid fibers have several useful characteristics:

- high strength and modulus;
- temperature stability;
- flex performance;
- dimensional stability;
- chemical resistance; and
- textile process ability.

Textile (continuous filament) glass fibers are the type used in composite reinforcement. These fibers differ from the wool type in that they are die-drawn rather than spun. A number of solvents are used in the advanced composites industry. These may be introduced into the workplace in three basic ways:

- as part of the resin or curing agent;
- during the manufacturing process; or
- as part of the clean-up process.

Most of the solvents used may be introduced in any or all of the three ways above. For this reason it would be difficult, if not impossible, to separate the solvents into the categories of use. The solvents discussed in this section are grouped by chemical class:

- ketones
- alcohols
- chlorinated hydrocarbons
- others

Several solvents may be used in any one composite process. One or more may be introduced as part of the resin or curing agent, while another may be a part of the manufacturing process. Still another may be used for clean-up. Thus, the hazard information for all products used in the process must be considered when evaluating potential exposures. The supplier's Material Safety Data Sheet (MSDS) should be consulted for more specific hazard information [17].

C. Resins

The resin systems used to manufacture advanced composites are of two basic types: thermosetting and thermoplastic. Thermosetting resins predominate today, while thermoplastics have only a minor role in manufacturing advanced composites. Thermoset resins require addition of a curing agent or hardener and impregnation onto a reinforcing material, followed by a curing step to produce a cured or finished part. Once cured, the part cannot be changed or reformed, except for finishing [21]. Some of the more common thermosets include:

- epoxies
- polyurethanes
- phenolic and amino resins
- bismaleimides (BMI, polyimides)
- polyamides

Of these, epoxies are the most commonly used in today's PMC industry. Epoxy resins have been in use in U.S. industry for over 40 years. The basic epoxy compounds most commonly used in industry are the reaction product of epichlorohydrin and bisphenol-A. Epoxy compounds are also referred to as glycidyl compounds. There are several types of epoxy compounds including glycidyl ethers (or diglycidyl ethers), glycidyl esters and glycidyl amines. Several of these compounds are reactive diluents and are sometimes added to the basic resin to modify performance characteristics. The epoxy molecule can also be expanded or cross-linked with other molecules to form a wide variety of resin products, each with distinct performance characteristics. These resins range from low-viscosity liquids to high-molecular weight solids. Typically they are high-viscosity liquids [17].

Since epoxies are relatively high molecular-weight compounds, the potential for respiratory exposure is fairly low. The potential for respiratory exposure is increased when the resin mixture is applied by spraying or when curing temperatures are high enough to volatilize the resin mixture. The potential for dermal exposure is typically much greater than respiratory exposure when working with epoxies. Several advanced composite processes involve some worker contact with the resin mixture. The second of the essential ingredients of an advanced composite system is the curing agent or hardener. These compounds are very important because they control the reaction rate and determine the performance characteristics of the finished part. Since these compounds act as catalysts for the reaction, they must contain active sites on their molecules. Some of the most commonly used curing agents in the advanced composite industry are the aromatic amines. Two of the most common are 4,4’-methylene-dianiline (MDA) and 4,4’-sulfonyldianiline (DDS). Like the epoxies, these compounds have a very low vapor pressure and usually do not present an airborne hazard unless in a mixture that is sprayed or cured at high temperatures. However, potential for dermal exposure is frequently high. The aromatic amines may permeate many of the commonly used protective gloves and thus may be particularly difficult to protect against [17, 18].

Several other types of curing agents are also used in the advanced composite industry. These include aliphatic and cycloaliphatic amines, polyaminoamides, amides, and anhydrides. Again, the choice of curing agent depends on the cure and performance characteristics desired for the finished part. Polyurethanes are another group of resins used in advanced composite processes. These compounds are formed by reacting the polyol component with an isocyanate compound, typically toluene diisocyanate (TDI); methylene diisocyanate (MDI) and hexamethylene diisocyanate (HDI) are also widely used. While the polyols are relatively innocuous, the isocyanates can represent a significant respiratory hazard as well as a dermal hazard. Phenolic and amino resins are another group of PMC resins. With respect to the phenol-formaldehyde resins, the well-known hazards of both phenol and formaldehyde must be protected against. In addition to traces of free formaldehyde, they may also contain free phenol, and contact with these resins in the uncured state is to be avoided. The urea- and melamine-formaldehyde resins present similar hazards. Free formaldehyde, which is present in trace amounts and may be liberated when their resins are processed, can irritate the mucous membranes. The bismaleimides and polyamides are relative newcomers to the advanced composite industry and have not been studied to the extent of the other resins [17]. Thermoplastics currently represent a relatively small part of the PMC industry. They are typically supplied as nonreactive solids (no chemical reaction occurs during processing) and require only heat and pressure to form the finished part. Unlike the thermosets, the thermoplastics can usually be reheated and reformed into another shape, if desired.

IV. MANUFACTURING TECHNOLOGY OF ADVANCED COMPOSITES

The industry can be generally divided into two basic segments, industrial composites and advanced composites. Several of the composites manufacturing processes are common to both segments. The industrial composites industry has been in place for over many years in the world. This large industry utilizes various resin systems including polyester, epoxy and other specialty resins. These materials, along with a catalyst or curing agent and some type of fiber reinforcement (typically glass fibers) are used in the production of a wide spectrum of industrial components and consumer goods and a variety of other parts and components. This sector of the composites industry is characterized by the use of expensive, high-performance resin systems and high-strength, high-stiffness fiber reinforcement. The aerospace industry, including military and commercial aircraft of all types and also wind turbine blades industry, is the major customer for advanced composites [17].

The feature common to all composite processes is the combining of a resin, a curing agent, some type of reinforcing fiber, and in some cases a solvent. Typically, heat and pressure are used to shape and "cure" the mixture into a finished part. In composites, the resin acts to hold the fibers together and protect them, and to transfer the load to the fibers in the fabricated composite part. The curing agent, also known as hardener, acts as a catalyst and helps in curing the resin to a hard plastic. The technology used in manufacturing wind turbine blades has evolved over the past 20-plus years (Fig. 12).

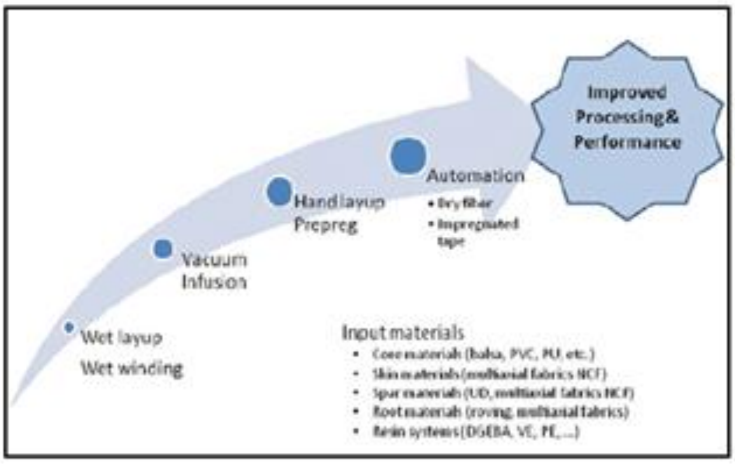


Fig. 12 Evolution of wind turbine production [22]

Blade making has migrated toward processes that minimize cycle time and reduce both cost and the probability of defects. Early blade building techniques grew out of the boat building industry, using processes that were high in labor and prone to inconsistencies and defects. Vacuum infusion took blade manufacturing technology to a higher level, with improvements in consistency and performance of a blade. Prepreg - or “pre-impregnated” - technology further enhanced blade performance by combining resins and reinforcements in a more rigorously controlled manner before placement in the blade mold. Today the trend is toward Automated Tape Layup (ATL) or Automated Fiber Placement (AFP) to reduce labor and improve quality, whether one uses dry fiber or prepreg tape (Fig. 12) [22].

The basic advanced composite manufacturing which is using wind turbine blades process types are described below.

A. Resin formulation consists of mixing epoxy or other resins with other ingredients to achieve desired performance parameters. These ingredients may be curing agents, accelerators, reactive diluents, pigments, etc.
B. Prepregging involves the application of formulated resin products, in solution or molten form, to a reinforcement such as carbon, fiberglass or aramid fiber or cloth. The reinforcement is saturated by dipping through the liquid resin (solution form, see Fig. 13) or by being impregnated through heat and pressure (hot melt form, see Fig. 14).

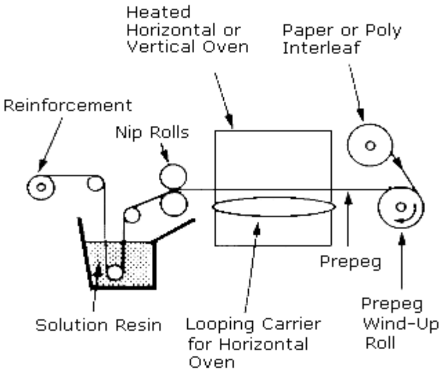


Fig. 13 Solution prepegging [17]

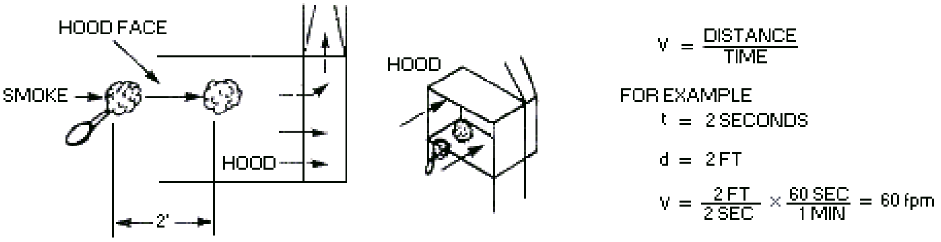


Fig. 14 Hot melt prepegging [17]

In the filament wet winding process, continuous fiber reinforcement materials are drawn through a container of resin mixture (Fig. 15) and formed onto a rotating mandrel to achieve the desired shape. After winding, the part is cured in an oven [23].

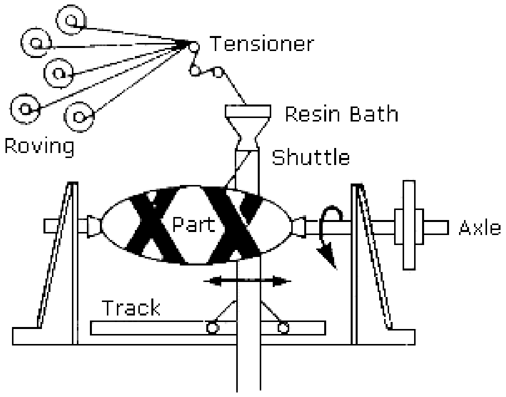


Fig. 15 Wet filament winding [17]

A prepreg product is laid down and formed to the desired shape (Fig. 16). Several layers may be required. After forming, the lay-up assembly is moved to an autoclave for cure under heat, vacuum and pressure.

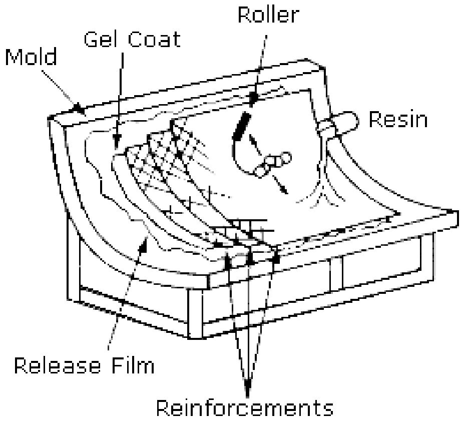


Fig. 16 Hand lay-up of prepreg [17]

In automated tape lay-up process, the prepreg tape material is fed through an automated tape application machine (robot). The tape is applied across the surface of a mold in multiple layers by the pre-programmed robot (Fig. 17).

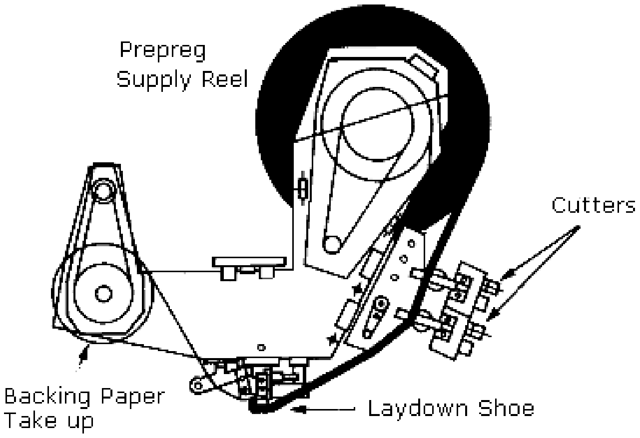


Fig. 17 Automated lay-up [17]

Most parts made by hand lay-up or automated tape lay-up must be cured by a combination of heat, pressure, vacuum and inert atmosphere. To achieve proper cure, the part is placed into a plastic bag inside an autoclave (Fig. 18). A vacuum is applied to the bag to remove air and volatile products. Heat and pressure are applied for curing. Usually an inert atmosphere is provided inside the autoclave through the introduction of nitrogen or carbon dioxide. Exotherms may occur if the curing step is not done properly.

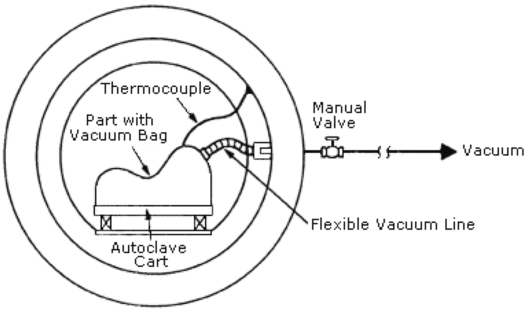


Fig. 18 Vacuum bagging and autoclave [17]

Many of the parts made in advanced composite processes require some machining and/or finishing work. This may involve drilling, sanding, grinding or other manual touch-up work. These processes vary widely, depending on the size of the finished part and the amount of finishing work required. Repair of damaged advanced parts is frequently required. The process may consist of several steps including cutting out of the damaged material, depainting of the surface to be repaired, patching and sanding of the damaged area, and repainting of the repaired area [17, 23].

V. ECONOMIC ASPECT OF ADVANCED COMPOSITE MATERIALS

According to market experts, the global industry for composites materials is estimated to grow in the mid-single digits in the next five years. The two sectors that will drive this growth are anticipated to be aerospace and wind energy, expected to grow by 15.6% and 13.3% each year respectively (Fig. 19) [24].

A June 2012 report from AMI Consulting values the global composite wind turbine blade market at an estimated €4 billion in 2011, of which approximately €1.5 billion was raw materials. AMI calculates that the global demand for materials for the production of wind turbine blades grew by over 20% per annum in the last five years [25, 26].

Materials used to manufacture rotor blades for wind turbines are subject to special requirements. The number of load cycles and the load variability are far beyond what is encountered by other structures in aviation, shipbuilding and bridge building. The development of new materials is also driven by the economics of wind turbine design. To maximise return on investment, the average blade size is growing longer and heavier requiring greater quantities of raw materials. As blade length approaches 90 m, increased sophistication in blade design, materials and manufacture are required. A larger surface area of the blade effectively increases the tip-speed ratio of a turbine at a given wind speed, increasing the amount of energy that can be produced. An important goal of larger blade systems is to control blade weight. Since blade mass scales as the cube of the turbine radius, loading due to gravity constrains the systems with larger blades [25].

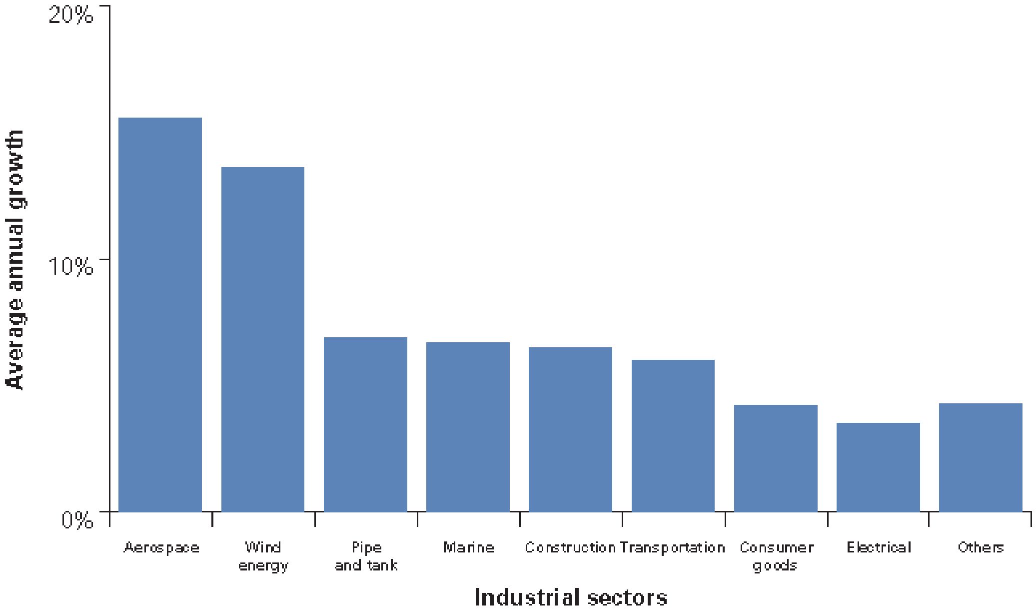


Fig. 19 Average annual global growth composite material forecasts by market segment, 2009-2014 [24]

Prepreg is a glass or carbon fiber reinforcement that is impregnated with resins such as epoxies. They are supplied in roll form and cured with the application of heat and pressure to produce high quality laminates with superior stiffness and strength – at low weights. Prepreg is an ideal cost-effective technology for the manufacture of large composite parts as the process is readily automated and the materials are easy to handle. Carbon fiber prepregs are a cost effective option for very large diameter blades, as less material is required to achieve the strength and stiffness of glass structures. Hybrid reinforcements of glass and carbon are also a potential option [19].

The global composite industry is becoming increasingly competitive. Market barriers exist that may hinder further commercial investment in composites and technological development. Economical focus is on advanced composites where it is believed that a competitive advantage can be built, there will be an increase in wind turbine blades market share of existing sectors and the use of composites in new industries is ensured [27].

Polymer matrix composites (commonly known as PMCs or fibre reinforced polymer/plastic – FRPs) have a wide range of properties depending on the fiber or matrix used. Most provide improved strength-to-weight ratios, stiffness-to-weight ratios, fatigue properties and corrosion resistance, in comparison to other commonly used engineering materials such as aluminium alloys. Their manufacture often depends on the formulation and combination of component materials including chemicals from a highly-skilled and technically-advanced composites industry [19].

Manufacturing blades in the 40-50 m range involves proven fiberglass composite fabrication techniques. For larger blades – currently limited to about 73.5 m – advanced composite materials pioneered in the aerospace industry are being specified. Carbon fiber reinforced laminates offer the greatest stiffness and strength to weight ratio. Carbon fiber reinforced load-bearing spars can reduce weight and increase stiffness. These benefits increase as blade size increase. The use of carbon fibers in 60 m turbine blades is estimated to reduce total blade mass by 38% and decrease cost by 14% compared to 100% fiberglass. One example of an advanced composite is carbon fiber reinforced plastic (CFRP). This has long been used in technology-intensive applications such as wind turbine blades due to its significant strength, stiffness and weight advantages over other engineering materials. Solutions focused on reducing the cost and time to manufacture CFRP components could make composites a more viable substitute for other materials. Carbon fibers have the added benefit of reducing the thickness of fiberglass laminate sections, further addressing the problems associated with resin wetting of thick lay-up sections. Wind turbines also benefit from the general trend of increasing use and decreasing cost of carbon fiber materials [25].

As we move towards a low carbon economy, it will become critical to consider the whole life impacts of innovative materials, from feedstock and manufacture to end-of life options. While composites in general possess many attributes that contribute favourably to a low carbon agenda, through the reduction of energy consumption in transport due to light weighting and the elimination of electrochemical corrosion, their role in developing sustainable products requires further work. Most resin systems are currently oil based, while both carbon and glass fibers are produced using energy intensive processes.

VI. CONCLUSIONS

The economics and the benefits of renewable sources of energy and in particular wind power are becoming increasingly convincing across the globe. Wind has the advantages of stable generation costs, low operating costs, renewable, short energy payback, less time-to-market, abundant resource and environmentally preferable. Latest technological developments taking place in the area of reliability of wind turbines and improvements in the properties of the materials used will make wind energy more competitive in the next decade.

Wind turbine blades must be strong enough to withstand the applied loads without failure; thus, the ultimate strength must be sufficient to with sustain extreme loads, and the fatigue strength must be sufficient to withstand the time-varying loads throughout the intended life of the blade. The blades must also be stiff enough to prevent collision with the tower under extreme conditions. Stiffness is also important locally for preventing buckling of those parts of the blade that experience compressive stresses. To minimize the cost of the power generated, the blade construction needs to be as light as possible; this has to be achieved through optimization of the structural arrangement and dimensions in accordance with the materials selection. The production processes used for manufacturing the blades must be sufficiently consistent and reliable to ensure that the end product is always compatible with the design assumptions and calculations.

Composites offer many advantages in wind turbine blade construction. Composites are also unique in their ability to be tailored for different properties using various reinforcement configurations, matrix materials and manufacturing processes. Wind turbine design has improved substantially due to composites technology, and as composite use becomes more common place there exists the need to minimize the time required to fabricate blades while tightening dimensional tolerances and repeatability. Many institutions are investigating and addressing these concerns in an attempt to improve the manufacturability of wind turbine blades.

Advanced composites like fiber-reinforced composites of the type used in wind turbine blades are laminates composed of several layers of reinforcing fabric impregnated with and held together by an adhesive resin. Such laminates can be very strong and stiff when loaded in their own plane, but are much weaker when loaded out-of-plane because the layers, or plies, can more readily be pulled apart. The in-plane properties are largely determined by the fibers, whereas the out-of-plane properties depend heavily on the strength and adhesive capability of the resin matrix [23, 26]. Increasingly enabled by the introduction of newer polymer resin matrix materials and high performance reinforcement fibers of glass, carbon and aramid, the penetration of these advanced materials has witnessed a steady expansion in uses and volume. The increased volume has resulted in an expected reduction in costs.

To improve materials for wind turbine blades, one should do things a little differently.

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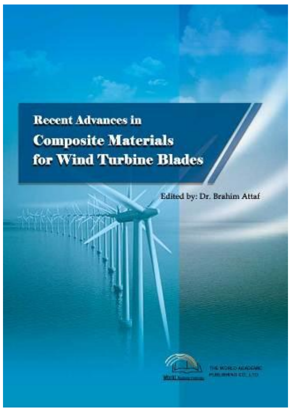

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