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Review on Hybrid Yarn, Structure and Techniques

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1. BACKGROUND

The demand of lightweight solutions is continuously increasing in many industries like transportation, offshore industries and the sports world. Composite materials can be an ideal solution for those industries. Due to fiber orientation and content can be adapted specifically to the load cases, resulting in weight reduction. In addition, fiber reinforced thermoplastic composites can be reprocessed, recycled and repaired when failure occurs through polymer chain pull out. Various polymers can be used as matrix system for composite applications. Selection of composites is due to their cost-effectiveness, chemical and/or mechanical properties. Various processes that can produce fiber reinforced thermoplastic parts are hand lay-up with autoclave molding, fusion bonding, press molding, diaphragm forming, liquid composite molding, roll forming, automated tape placement, filament winding and automated tape winding [1].

1.1 Fiber Forms

Many types of reinforcement fibers are currently available. The fibers that have been used include glass, aramid, carbon (graphite) and boron. Reinforcements like ceramic fibers, metallic fibers, and whiskers have also been used in specific applications. Glass fibers are produced by mixing various ingredients in specific proportions, melting the mixture in a furnace, and drawing molten glass in the form of filaments. The proportions of various ingredients depend on the product form desired. E glass fibers are used in electrical applications and S glass fibers are used in strength critical situations. S glass fibers are sometimes woven in composite materials to increase toughness and impact resistance. Carbon or graphite fibers are produced by pyrolytic degradation of an organic precursor material. The commonly used precursor materials include polyacrilonitrile (PAN), rayon and pitch. The fibers produced from PAN precursor are high strength and low modulus, whereas pitch fibers are high modulus and low strength. Carbon fibers contain 92 to 99 percent carbon and graphite fibers contain 99 percent carbon. Aramid fibers are aromatic polyamide fibers made from a polymer solution that is pressure extruded into a chemical bath by a procedure standard for synthetic textiles fibers. Commercially available fibers are Kevlar 29, Kevlar 49 and Nomex. Boron fibers are obtained by depositing elemental boron over a tungsten substrate, using chemical vapor plating. Boron fibers are larger in size as compared to glass, carbon and aramid fibers. The reinforcement fibers are generally available in the form of a tow, or in a band as shown in Figure 1. A woven form of the reinforcements is also used in certain cases, depending on the application of the composite.

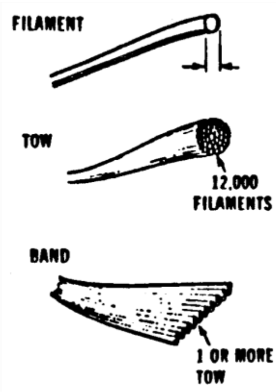


Figure 1 Fiber Forms

1.2 Hybrid Yarns

Hybrid yarns consisting of reinforcing and matrix fibers are one kind of basic material (semi-finished product) with which continuous fiber reinforced thermoplastic composites can be constructed [2, 3]. Composite properties are influenced mainly by the arrangement of the reinforcing fibers and the homogeneity of the fiber distribution in the composite, as well as by impregnation of the glass fibers with the polymer matrix. Hybrid yarns are usually manufactured into thermoplastic composites by hand lay-up [4], filament winding [5, 6] or—as done recently—by the pultrusion process [7].

The hybrid yarns were manufactured on the basis of glass and polyamide fibers, the properties of which are summarized in Table 1. The fineness of the fibers is given in Tex (tex¼ g/1000 m). From these filaments, hybrid yarns have been produced by different technologies, resulting in different structures of the semi-finished product:

- Parallel arrangement of glass and polyamide fibers (side by-side, SBS);
- Parallel arrangement of matrix fibers surrounded by parallel glass fibers in the core, sheathed by matrix fibers in the skin (‘Kemafil’ technology, KEM);
- Commingled glass and polyamide fibers made by air texturing (commingled yarn, COM);
- Parallel arrangement of glass fibers in the core and spun matrix fibers in the skin (friction spinning, FS); and
- Mixture of glass and matrix fibers, both discontinuous, surrounded by a continuous matrix filament (Schappe technology, SCH).

Table 1 Hybrid yarn structures and corresponding production technology [6].

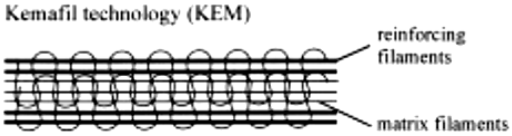
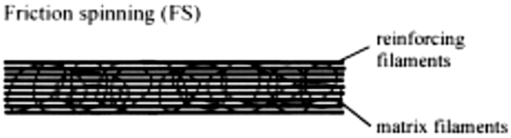
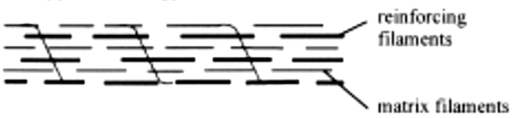
Technology	Geometry of fibre arrangement
Parallel winding of reinforcing and thermoplastic matrix filaments (side-by-side, SBS) 	parallel arrangement of reinforcing and matrix filaments
Kemafil technology (KEM) 	parallel arrangement of matrix fibres sourrounded by parallel reinforcing fibres in the core, sheathed by matrix fibres in the skin
Air texturing (COM) 	reinforcing and matrix fibres are commingled; the arrangement of reinforcing fibres is out of yarn axis
Friction spinning (FS) 	parallel arrangement of reinforcing fibres in the core and spun fibres in the skin
Schappe technology (SCH) 	mixture of discontinuous reinforcing and matrix fibres sourrounded by continuous matrix filaments

Table 2 Basic materials for manufacturing hybrid yarns [6].

	SBS	KEM	COM	FS	SCH
Glass					
Filament diameter (μm)	10	10	10	9	10
Fineness of filament yarn (tex)	40	40	40	135	–
Polyamide 6					
Fibre fineness (dtex)	–	–	–	1.3	–
Fineness of filament yarn (tex)	40	40	40	–	–
Hybrid yarn					
Glass:polyamide (mass%)	60:40	66:34	66:34	67:33	72:28
Fineness (tex)	200	1440	720	200	588
Producer	IPF	IPF	IPF	ITA[a]	Schappe[b]

[a]Institut für Textiltechnik der RWTH Aachen
[b]prospectus Schappe Techniques

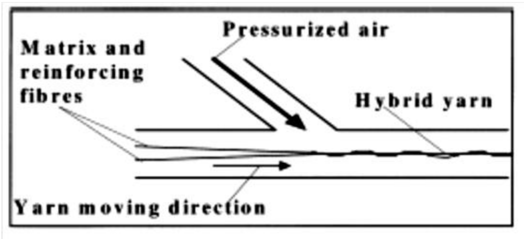
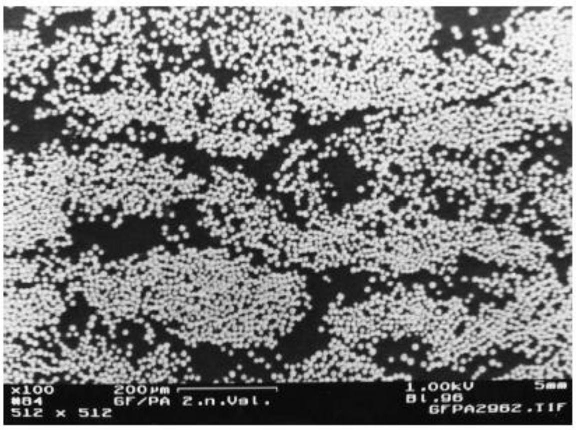


Figure 2 Principle of air texturing to produce commingled yarn (COM) [6].

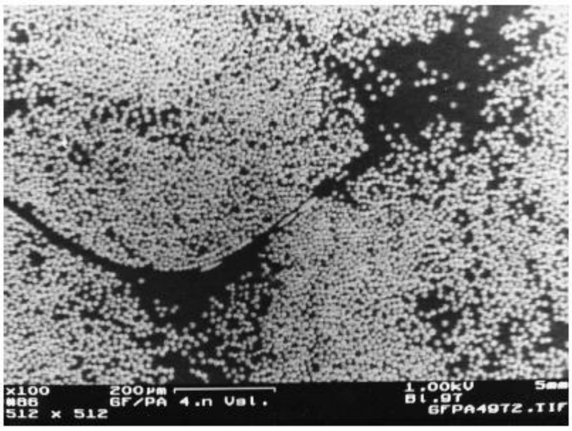
The air-texturing process for the production of commingled yarn is demonstrated in Figure 2. The reinforcing glass fibers and the polyamide matrix fibers are subjected to pressurized air while moving through the texturing device. The air turbulence causes mixing of glass and polyamide fibers, resulting in the commingled yarn.

1.3 Kemafil Technology

The 'Kemafil' technology is a turning thread technique. By means of mechanical interlacing of yarns into a knitted structure, linear textiles are produced (laces, strings, cords and ropes). Kemafil machines are circular knitting machines operating with loopers that are arranged around a guide tube and give a tubular knitted structure which can cover any type of core yarn. SBS yarns are made much more simply by parallel winding of reinforcing and matrix fibers and give a tubular knitted structure which can cover any type of core yarn. SBS yarns are made much more simply by parallel winding of reinforcing and matrix fibers.



(a)



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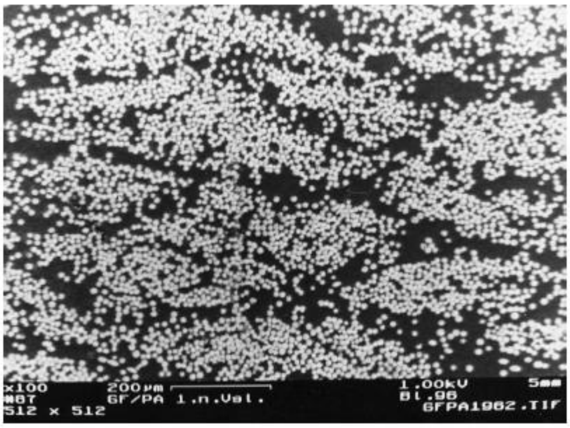

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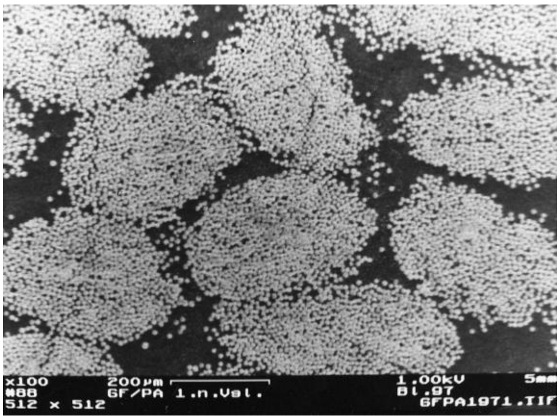

(d)

Figure 3 Micrograph of a polished area of (a) SBS composite (b) KEM composite (c) COM composite and (d) FS composite [6].

The SCH and COM composites show the best degree of mixing of reinforcing and matrix fibers. However, this is a merely qualitative description of the yarns' microstructure which influences more profound quantities that determine the consolidation quality of the composite. Impregnation of the reinforcing fibers with matrix material is determined mainly by the average flow distance of the polymer, a parameter that is also difficult to express quantitatively but one depending on the degree of mixing. The yarns may be ranked according to increasing flow distance as follows: SCH, COM, KEM, SBS and FS. Consequently one can expect that the impregnation quality of the glass fibers with polyamide matrix for the yarn structures investigated will be the highest for SCH composites and decrease towards FS composites. Another parameter is the possibility of fiber flow, i.e. the fibers themselves can move together with the matrix. In compression moulding of a flat plate, this movement is negligible for continuous yarns, which can be considered to be fixed. The Schappe yarn consists of discontinuous fibers and thus such movements are possible. If all of these parameters are compared, the Schappe and COM yarns come out best, being comparable, followed by SBS then KEM, and the worst material is the FS. This is reflected by a comparison of the micrographs of Figure 3 [6].

1.4 Compression Moulding

Composites consisting of 15 unidirectional laminate were manufactured by compression moulding. Hybrid yarns were wound with a filament winding device on a plate core and then consolidated under 3 MPa pressure at a temperature of 2458C into plates. These plates were cut into the different sample geometries necessary for the delamination and tension tests. Although efforts were taken to achieve composites with the same glass fiber volume fraction by using the same mass ratio between glass and polyamide fibers for each yarn, the resulting composites showed a variation in the glass fiber volume fraction. These fiber volume fractions were determined by the matrix burn-off method for some parts of the specimens [6].

2. HIGH PERFORMANCE COMPOSITES IN TEXTILES

Composites consisting of fillers in the form of inorganic/organic fiber or powder as well as metallic powders of relatively high strength and modulus embedded in or bonded to a matrix with distinct interface between them. Most usual fillers are fibers. Both fillers and matrix retain their physical and chemical identities, and they produce a combination of properties that cannot be achieved with either of the constituents acting alone.

In the recent years, the use of textile structures made from high performance fibers is finding increasing importance in composites applications. In textile process, there is direct control over fiber placements and ease of handling of fibers. Besides economical advantages, textile preform technologies also provide homogenous distribution of matrix and reinforcing fiber. Thus, textile preforms are considered to be the structural backbone of composite structures [1]. This technology is of particular importance in the context of improving certain properties of composites like inter-laminar shear and damage tolerance apart from reducing the cost of manufacturing.

Textile industry has the necessary technology to weave high performance multifilament fibers, such as glass, aramid and carbon, which provide high tensile strength, modulus, and resistance to chemicals and heat to various types of preforms. Depending upon textile preforming method, the range of fiber orientation and fiber volume fraction of preform vary, subsequently affecting the matrix infiltration and consolidation. As a route to mass production of textile composites, the production speed, material handling and material design flexibility are major factors responsible for the selection of textile reinforcement production. This opens a new field of technical applications with a new type of semi-finished material produced by textile industry.

The basic element of reinforcement is the single fiber or filament. In the case of short fiber composites, the continuous filaments are cut into specific length and then mixed with the resin using a suitable process. For example, in the case of injection molding, the short fibers are mixed with polymers and then the mixture is injection molded. The short fibers are also used as chopped strand mats. The mat is used primarily in hand lay-up, continuous lamination and some closed molding applications. Figure 4 shows the schematic diagrams of the chopped strand and continuous strand mat. Swirling of continuous strands of fibers onto a moving belt forms continuous strand mat. The mat is finished with a chemical binder that holds the fiber in place. Continuous strand mat is primarily used in compression molding, resin transfer molding and pultrusion applications as well as to fabricate preforms and stampable thermoplastics.

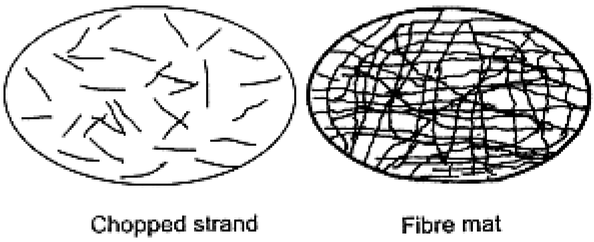

Figure 4 Forms of reinforcement [8].

Another form of reinforcement is known as roving. A roving refers to a collection of untwisted strands or yarns. The glass strands are wound together to form a roving package suitable for internal or external unwinding. The roving is tailor made to suit specific applications with polyester, epoxy and vinyl ester resin systems. It can also be used for compounding with various thermoplastics and to produce a wide variety of reinforcing materials, including mats, woven fabrics, braids, knitted fabrics and hybrid fabrics.

Prepregs are another class of reinforcement in which the fibers and resin are already mixed together. Advantages of prepregs include faster curing, improved distribution of resin throughout the part, cleaner manufacturing facilities, more precise fiber alignment and placement, ability to use higher fiber contents and, therefore, less resin overall, and ability to lay-up the material into some shapes that would be difficult with wet systems. Flexible prepregs, like powder-impregnated tows, commingled yarns and core spun yarns are used for textile preforming operations. The present paper reviews the developments made in the field of textile preforms along with their advantages and disadvantages.

2.1.1 Semi-Finished Products

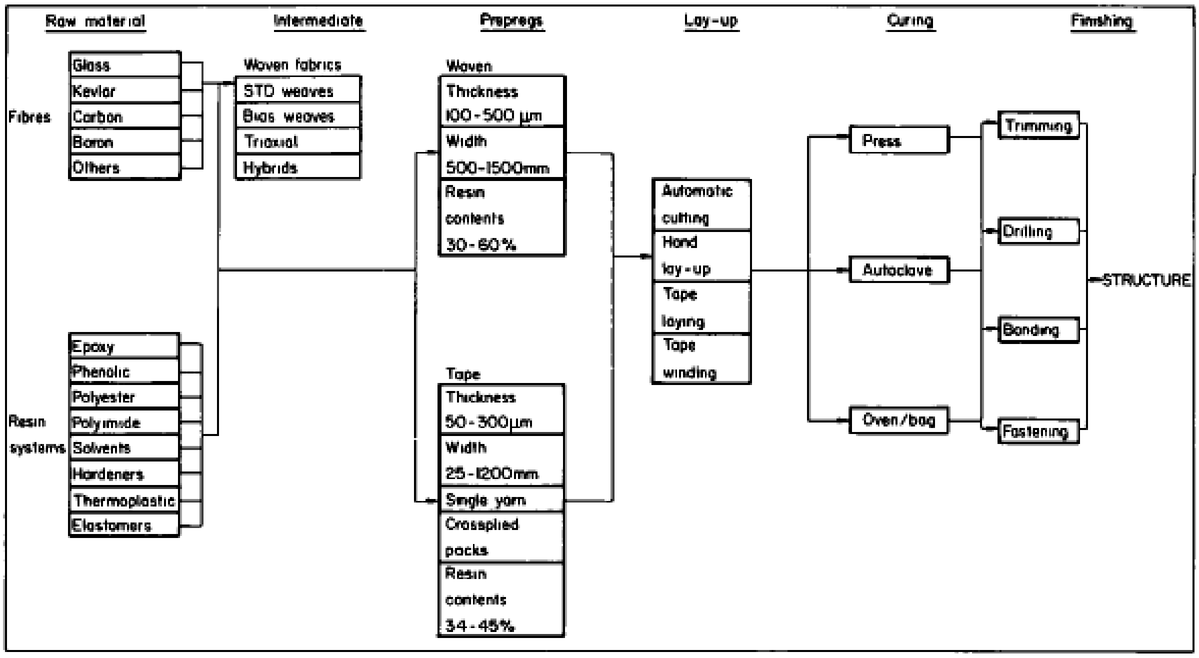

Figure 5 Flow chart showing key stages in the fabrication of composite structures from raw materials

A filament is a single segment of reinforcement. Tow count is the number of filaments in the carbon fiber bundle which can vary such as 3K, 6K, 12K, 24K, and 50K tow fibers. Smaller tow count carbon fibers are generally of higher strength and modulus compared to standard modulus 50K tow carbon fibers commonly used for less demanding non-aerospace applications. Standard modulus carbon fibers are generally of 12K-50K tow size range and constitute 80-90% of the total carbon fiber market today. A filament can be used in continuous fiber processes such as filament winding and pultrusion. Filaments may also be woven or stitched into fabrics. Preforms are three-dimensional fabric forms designed to conform to a specific shape to meet specific mechanical and structural requirements. A pre-impregnated composite, or pre-preg, is where fibers, often in the form of a weave or fabric, are held together with a matrix resin. The matrix is partially cured to allow easy handling but must be cold stored to prevent complete curing. Bulk Molding Compounds (BMC) are primarily the crosslinking thermoset materials which are widely used in low-end composite applications today. Sheet Molding Compounds (SMC) are thin sheets of fibers pre-compounded with a thermoset resin and is primarily used in compression molding processes.

3. TEXTILE PREFORMS FOR COMPOSITES

3.1 Woven Preforms

Developments in the field of preforming have led to the production of preforms with fibers orientated in different directions with weaving, knitting and braiding individually or in combinations. Table 3 provides a comparative account of different preforming techniques with respect to yarn direction and fabric formation principles. While 2D woven textile structures are usually formed into shape by molding or stitching, 3D textile preforms are more suitable for the creation of net-shaped thicker structures. Very good drapability and complex shape formation with no gap and reduced manufacturing cost are the main features of woven fabrics. The plain woven fabric is symmetrical with good stability and reasonable porosity. However, it is the most difficult of the weaves to drape, and the high level of fiber crimp imparts relatively low mechanical properties as compared to the other weave styles. With thick fibers, this weave style gives excessive crimp and, therefore, it tends not to be used for very heavy fabrics. In twill fabrics, the warp yarns alternately weave over and under two or more weft yarns in a regular repeated manner. Superior drape is observed in the twill weave over the plain weave with only a small reduction in stability. With reduced crimp, the twill fabric also has a smoother surface and slightly better mechanical properties. Satin weaves are fundamentally twill weaves modified to produce fewer inter-sections of warp and weft. Therefore, the low crimp gives good mechanical properties. Satin weaves allow fibers to be woven in the closest proximity and are capable of producing tight and compact preforms [9].

Table 3 A comparison among different fabric formation techniques [8].

Parameter	Direction of yarn introduction	Fabric formation principle
Weaving	Two ($0^{o}/90^{o}$) (warp and weft)	Interlacing (By selective insertion of 90^{o} yarns into 0^{o} yarn system)
Knitting	One ((0^{o} or 90^{o}) (warp or weft)	Interlooping (By drawing loops of yarns over previous loops)
Braiding	One (machine direction)	Intertwining (Position displacement)
Nonwoven	Three or more	Mutual fiber placement

(orthogonal)

Basket weave is fundamentally the same as plain weave except that two or more warp fibers alternately interlace with two or more weft fibers. Basket weave is flatter due to less crimp. Although the basket weave is stronger than a plain weave, it shows poor stability than plain woven fabrics. Basket weave can be used to develop heavy weight fabrics from thick fibers to avoid excessive crimping. Leno weave improves the stability in open fabrics which have a low yarn count. Leno woven fabrics are normally used in conjunction with other weave styles, because if used alone, their openness does not produce an effective composite component. Triaxial weaves show high levels of isotropy and dimensional stability even at low fiber volume fraction [9, 10]. The characteristics of some woven preforms are compared in Table 4.

Table 4 A comparative properties of some woven preforms [8].

Property	**Woven preform**					
	Plain	Twill	Satin	Basket	Leno	Mock-leno
Higher stability	4	3	2	2	1	3
Good drape	2	4	5	3	5	2
Low porosity	3	4	5	2	1	3
Smoothness	2	3	5	2	1	2
Balance	4	4	2	4	2	4
Low crimp	2	3	5	2	5	2

Rating scale: (5) Excellent (4) Very good (3) Good (2) Poor (1) Very poor

Weaving is extensively used in the composite industry, as it produces the vast majority of single layer, broadcloth fabric which can be used as reinforcement. The poor impact performance reduces in-plane shear properties, and the poor de-lamination resistance of such structures has led to the use of stitching techniques. In addition to weave crimp, stitching is often considered as a factor which reduces the mechanical efficiency of reinforcing fibers [11]. With some modifications, the standard industry machines can be used to manufacture flat, multi-layer fabrics of wide variety of structures which have highly improved impact performance. Multi-axial 3D weaving apparatus has also been reported. Bias yarns sandwiched between weft yarns and the resulting assemblies bound together by warp yarns have produced unique structures. However, the main disadvantage of these multi-layer fabrics is that the standard looms cannot produce fabric that contains in-plane yarns at angles other than 0° and 90° [12]. This results in structures having very low shear and torsion properties, thereby making them unsuitable in many aircraft structures where materials with anisotropic properties are required. To overcome this problem, a great deal of effort has been made for the development of looms that can produce fabric with ±45° fibers [13].

Several weaving techniques have been reported to produce multi-axial multi-layer 3D preforms. These include lappet weaving, tri-axial weaving and pile weaving [11, 13, 14]. Lappet weaving is a special technique in which extra warp threads are introduced traditionally to develop isolated design motifs on open weave background. A standard weaving machine can be modified to incorporate lappet system to develop integrally woven multi-axial multi-layer preform structures for composites. The extra warp yarns (bias yarns) can be made to run at any angle between wrap and weft directions. To get the through-the-thickness reinforcements, the extra warp yarns can be interlaced with weft yarns at any position within a multi-layer structure with the two extremes corresponding to weft yarns at the same and opposite fabric surfaces. However, the location of extra warp yarn which is limited to the outer surface of preform and the control of lappet bar movement in the reverse direction are the main limitations to develop multi-layer preforms on lappet weaving machines.

Triaxial multi-layer fabric structures for composite reinforcements can be developed by inclusion of axial warp yarns as a third warp set in the basic triaxial process. However, the modification of triaxial weaving machine to incorporate such yarns would be a major engineering task. A patent [15] also describes the use of a jacquard shedding mechanism to manufacture multi-layer woven textile preforms. Greenwood et al. [16] described a method to develop stress oriented T-shaped woven preforms for composites. To develop T cross-sections, two sets of parallel threads at right angles to each other and at 45° angle to warp are required. To achieve correct orientation of threads, two sets of weft threads have been used to form this angle separately. This can be done by joining of two layers either along one side or side-by-side.

The typical examples of 3D woven fabrics are simple interlock, orthogonal and complex shaped structures. Different multi-layer 3D woven structures and multi-axial pile fabrics are shown in Figure 6. Using the multi-warp weaving method, various fiber structures can be developed including solid orthogonal panel, variable thickness solid panels and core or truss like structures. Orthogonal cross-lapped fabrics can be formed by the placement of yarns at right angle to each other, typically in either rectangular or cylindrical space. There is no interlacing or other form of entanglement to hold the structure. Yarn is alternately laid between the edges in alternating orthogonal direction to create thick structure [8].

3.2 Knitted Preforms

Flat knit and shape knit products show the ability of the knitting process to manufacture complex shaped components. Jet engine vanes, T-shaped connectors, medical prosthesis, car wheel wells and aerospace fairings have all been successfully manufactured. The structure of yarn in the preform is highly curved and the interlooping of yarn permits a very elastic and flexible structure. This is an advantage where components of complex shape without crimp are required and better formablity and drapability of preforms are critical. Because of good drapability, a high degree of deformation can be possible.

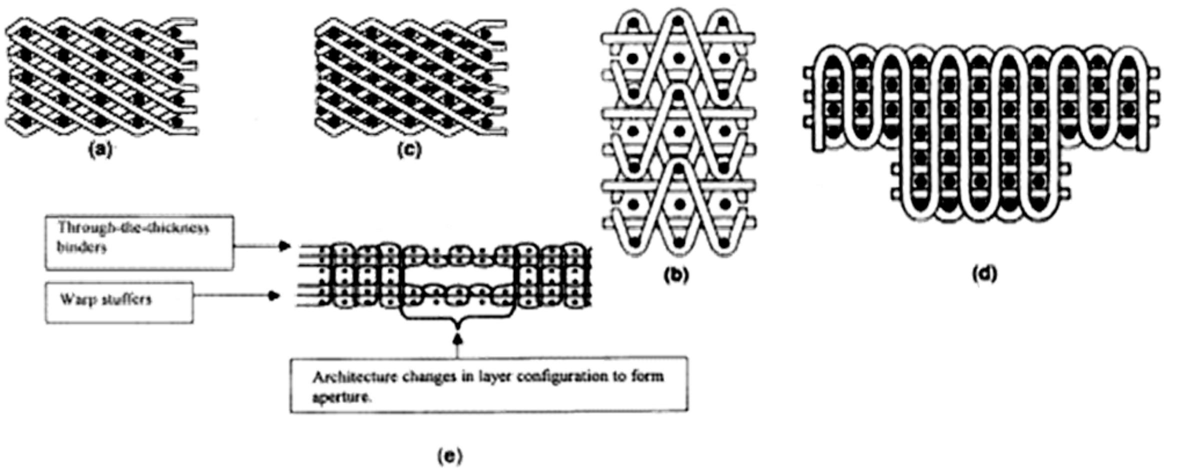

Figure 6 Multi-layer 3D weave and its variants (a) multi-layer 3D weave, (b) change of angle, (c) angle interlock, (d) variable thickness solid panel, and (e) near net shaped preform [8].

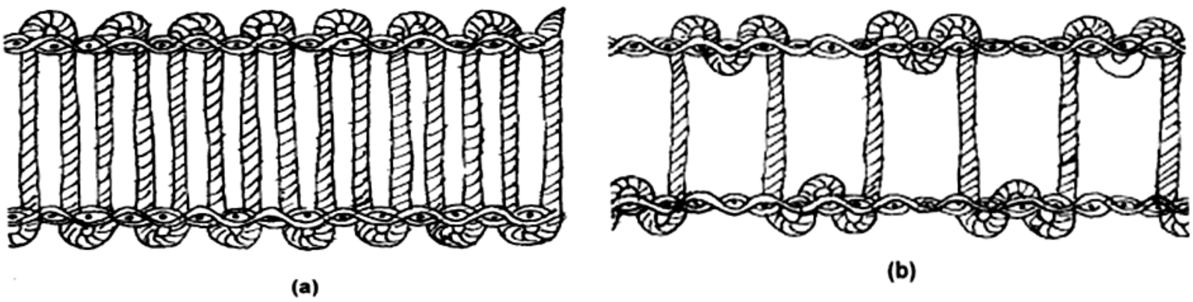

Figure 7 Pile interlacing patterns (a) V interlacing, and (b) W interlacing [8].

Table 5 Comparison among different multi-axial weaving techniques [8].

Bias fiber placement	Uniformity of bias fiber layers	Through-the-thickness reinforcement	Multiple layers
Rapier	No	Yes	Yes
Lappet	Yes	No	No
Screw shaft	No	Yes	Yes
Split reed	Yes	Yes	Yes
Guide Block	Yes	Yes	Yes
Bobbin (polar)	Yes	Yes	Yes

The yarn structure of the knit also tends to improve the impact performance of the composites; however, the structural performance of knitted composites is generally low. Hong et al. [17] described the various methods to develop 3D shaped knitted preforms, including tubular, spherical and box forms, by using SES 122FF flat knitting machines. 3D shapes can be developed by using a variety of structural combinations, such as different loop lengths and alteration in the number of knitting needles and courses. Wilde and Zigmann [18] compared woven fabric, outstretched glass/polyester (GF/PET) knit and 73% pre-stretched GF/PET knit. GF/PET co-knitted fabrics have been developed by simultaneous knitting of glass and polyester yarns. They also developed a weft knitted preform from GF/PET commingled yarns and observed that the stiffness of knitted fabric is more isotropic than that of woven fabrics. Further, they commented that the size of loops in knitted fabrics would determine the strength and stiffness of composites.

The properties of flat knitted fabrics are different from those of other textile preforms. This area of knitting does overcome the problem of poor mechanical performance and it is the subject of intense interest within the aerospace industry. Woven and multi-axial fabrics are stiffer than conventional knitted fabrics and therefore more suitable for high performance applications where high tenacity and lower strains are required. With insertion of weft inlay threads, the stiffness of these fabrics can be increased.

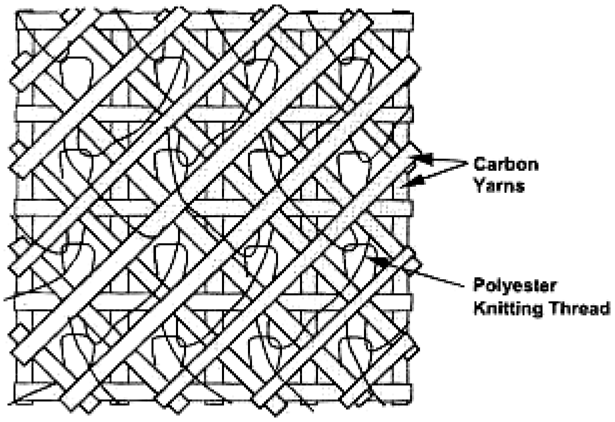

Figure 8 Multi-axial warp knit (MWK) structure [8].

By using warp knitting techniques in conjunction with fiber placement concepts, multi-layer fabrics can be produced containing straight and relatively uncrimped fibers stacked in the required orientations. Karl Mayer Textil machinen fabrik GmbH and LIBA Maschienen fabrik GmbH developed this technology. Figure 8 shows multi warp knitted (MWK) structure. MWK structure is produced on special raschel machine and the structure consists of two diagonal weft yarns, followed by a warp yarn and a horizontal weft yarn. The layers are held together by pillar stitches from both sides. The diagonal weft insertions ensure parallel placement of yarns at constant distance. Weft insertion makes it possible to arrange the least part of the fiber in stretched form. The diagonal angle of weft can be varied in the range of ±30°-60° by suitably altering the course density.

By using LIBA technique, multi-axial fabrics can be produced on a special tricot machine using 5-7 weft inlaid yarn layers and a warp inlaid yarn layer. At each weft station, the yarn can be laid horizontally in the range ±30°-60° and therefore easy interchangeability of layer positions is possible. LIBA technique gives Quadra-axial structures, where yarns are arranged at 0^{o}, $+45^{o}$, -45^{o} and 90^{o}. Malimo technique is another method to develop multi-axial stitch bonded knitted structures by stitching of several layers of yarns together at various angles or piles of skewed fabric on modified stitch bonding machine. This will improve mechanical properties and structural consistency [8].

In knitted multi-axial structures, materials for inlays are normally high modulus or high temperature resistant polymer filaments such as polyester, nylon and PEEK, whereas glass, aramid or carbon threads can be used as reinforcing fiber materials. The use of these fabrics can lead to cost savings in the manufacture of composite components and the uncrimped nature of the yarn can also produce improved mechanical performance when compared to traditional woven fabrics. These fabrics have excellent dimensional stability and outstanding in-plane shear resistance in all directions. The warp inlay multi-axial structures show higher elastic modulus compared to woven fabrics. Tear strength of warp inlay multi-axial structure is found to be higher than that of woven fabrics. This may be due to the shifting of yarn layers under force and bunch together to resist tearing.

3.3 Braided Preforms

Two-dimensional braided structures are intertwined fibrous structures capable of having 0^{o} and $\pm\theta$ fiber orientation. Thickness is built by over braiding on previously braided layers, similar to ply layup process. Braiding can take place vertically or horizontally but the majority of composite braids is horizontal. The braiding process is capable of forming quite intricate preforms and has been successfully used with glass, aramid, carbon, ceramic and metal fibers. The braiding process can be varied during operation to produce changes in the cross-sectional shape as well as tapers, bends and bifurcations. Due to the high level of comformability and damage resistance capability of braided structures, the composites industry has used the braided composites in various applications ranging from rocket launchers to automotive parts to aircraft structures.

By simply changing the relative position of carriers on track ring, different interlacing patterns can be produced. The pattern can be designed as 1/1 or diamond braid; however, the 2/2, 3/3 2/1 and 3/1 are the interlacing patterns of common use. Among all these patterns, 2/2 braid is the most popular and is referred as regular, standard, plain or flat braid. The braid has the tightest structure when each yarn is in contact with all neighboring yarns. However, due to bulky fiber structure and crimp, it is very difficult to form tightest structure. The braided structure enables the composite to endure shearing and impact better than woven preforms. Braids are continuously woven on the bias and have at least one axial yarn that is not crimped in the braiding process. This arrangement of yarns allows highly efficient load distribution throughout the braid. Either flat or tubular configurations are available as braids. Flat braids are used primarily for selective reinforcement, such as strengthening specific areas in pultruded parts. Tubular braid can be pultruded over a mandrel to produce hollow cross-sections in a variety of parts such as windsurfer masts, lamp and utility poles.

Braiding was the first textile process used to manufacture a 3D fiber preform for a composite. 3D braiding is an extension of 2D braiding in which the fabric, constructed by intertwining or orthogonal interlacing of yarns to form an integrated structure through position displacement, provides through-the-thickness reinforcement and ready acceptability to the fabrication of wide range of complex shapes. 3D braids show comparatively high level of fiber content and at the same time less than 1% voids by interlocking continuous layers of braid. There are basically two types of braiding machines, one is rectangular and other is circular, to produce I or T beams and thick wall tubular structures respectively. Furthermore, multiply preforms can be developed by interlacing adjacent layers on 3D braider. The key geometric parameters of 3D braids are fiber orientation, total fiber volume fraction, void and axial fiber percentage of total fibers. The speed ratio between braiding and take up as well as the linear density ratio of braider and axial yarn are the simple process parameters to adjust or control the microstructure of 3D braids.

Although 2D braided preforms offer numerous applications, the major limitation of 3D braiding is that the maximum preform size is determined by the braiding machine size and most available machines are only able to braid preforms with small dimensions only. Larger and more expensive machines will be needed to produce preforms suitable for a wider range of structural uses. Furthermore, many 3D braiding machines are still in a research and development stage and thus only a few machines are presently able to commercially manufacture preforms. 3D braiding machines are also slow and have short production runs. As a result, 3D braids cannot compete with 2D braids and laminates on a cost saving basis [8].

3.4 Stitched Preforms

Stitching of textile preforms is considered as one of the important techniques to develop complex textile preforms. The process of stitching can be used in two ways: Firstly, the stitching can be used simply as a way of assembling the single or multi-layered textile preforms together and holding them into the required shape during consolidation process. The second use of stitching is to improve the impact performance of composite structures by the addition of through-the-thickness reinforcement.

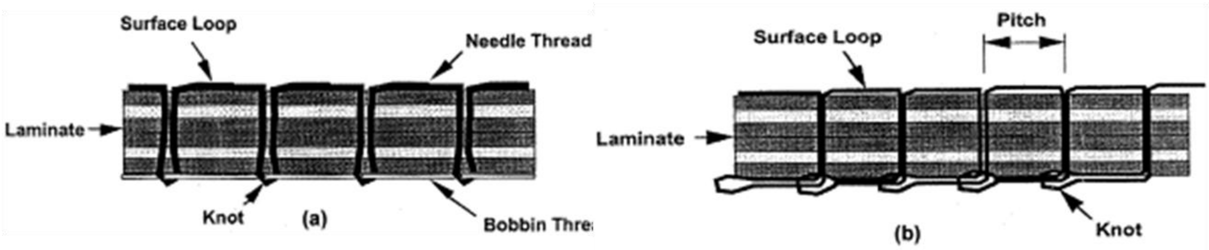

Figure 9 Different types of stitches for through the thickness reinforcements (a) lock stitch, and (b) chain stitch [8].

Stitching involves sewing high performance yarn (e.g. glass, carbon or Kevlar), through an uncured prepreg laminate or dry fabric plies using an industrial sewing machine. Stitching has also been performed using polyester thread, though Kevlar is the most popular yarn because of its high strength and flexibility. A variety of sewing machines can be used to stitch composites, although they can usually be classified as single-needle or multi-needle machines.

Figure 9 shows different types of stitches through-the-thickness of reinforcements. Stitching equipment currently used in the textile industry is capable of manufacturing preforms from aerospace-grade materials and a significant amount of research effort has been devoted to the performance of these stitched composites. Special attention is provided particularly in manufacture of complex shaped structures using stitching. Commonly available 2D fabrics are used as the main reinforcement in the structure. This provides large amount of flexibility in engineering textile structures to get the desired composite properties.

For making near net shape preform and joining textile reinforcement materials, stitching is very important tool. It makes preform material ready to use and easy to handle. However, the stitching of preform creates faults in the plane of material which affects the structural properties of composites and some of the reinforcement fabric related properties. This damage adversely affects the mechanical properties of composites. Weimer et al [19] studied the various parameters that affect the stitching process and observed that, in addition to the type of textile preforms and stacking sequence, the other parameters such as stitch direction, properties and appearance of thread material and stitching process strongly affect in-plane fiber distortion and compaction during stitching and impregnation process. Improved damage tolerance under impact and better post-impact mechanical properties have been major reasons for the burgeoning amount of research into stitched composites.

3.5 Nonwoven Preforms

Nonwoven structures are fiber-to-fabric assemblies produced by chemical, thermal or mechanical means or a combination of them. The thickness of sheet may vary from 25 μm to several centimeters and weight from 10 g/cm^2 to 100 g/cm^2. Nonwovens have density less than usually demanded in structural composites. As nonwovens become more readily available with the range of properties, the market for composites is also expected to increase. Composites made from nonwoven glass with epoxy resins reduce exfoliation between layers at high temperature. Nonwoven-based composites are finding increased application in automotive, marine and other applications.

Two very popular types of composites used in medical applications are SMS (Spun bond, Melt blown and Spun bond) and MSM (Melt blown, Spun bond and Melt blown) which in actual sense are laminate structures. A method to develop composite material by coating nonwoven fabrics made of carbon fiber or a blend of carbon fiber and other organic fiber with a filler-containing liquid has been described in a patent [20]. This low-priced pitch-based carbon fiber nonwoven can be used cost effectively in composites as friction materials, packaging and gasket applications. Composites developed from a nonwoven mat consisting of acrylic continuous filaments and impregnated with an inorganic matrix offer a wide range of applications in the fields of construction, aerospace, filtration, industrial, marine, medical protection, sports and transportation.

3.6 Characterization of Textile Preforms

The essential properties of textile preforms for composites include high flexibility, formability, stability and high axial rigidity. Table 6 shows some of the important properties of textile preforms. Consideration of geometrical properties in designing textile preforms will help to predict the resistance of preforms to mechanical deformation such as initial extension, bending and shear in terms of resistance to deformation of individual fibers. It will also provide the information regarding maximum achievable packing of a fabric.

Textile preforms are subjected to a wide range of complex deformations during manufacturing of composites. This includes intra- ply shear, inter-ply shear (if two or more plies are used), viscous friction between tool and material, inter-tow slip and applied pressure during consolidation. Some other serious problems are also observed during composite formation, such as wrinkling (buckling of fibers), and variations in fiber volume fraction due to spreading or bunching of fibers. The behavior of textile preforms extended at any angle involves the consideration of shear behavior of fabrics. Tensile forces along the fiber axis may lead to fiber straightening and compressive force can cause buckling.

Chen and Chou [21] studied the mechanical properties of multilayer and angle interlock woven structures and observed that the mechanical properties of 3D woven structures heavily depend on the fabric structure. Straight yarns in orthogonal weaves provide high tensile strength and stiffness and this is directly proportional to the number of layers of orthogonal weave. However, the breaking elongation of orthogonal woven structure is independent of weave and number of layers, as breaking elongation primarily depends upon the type of yarn used. Further, they stated that the shear rigidity and shear hysteresis depend on binding weaves. Shear rigidity and hysteresis increase with the increase in number of layers. They also observed that the tighter binding weaves and more layers of orthogonal structure would produce higher bending stiffness and bending hysteresis and vice versa. Finally, it is concluded that the straight yarns in orthogonal weaves provide high tensile strength and stiffness and this is directly proportional to the number of layers of orthogonal weave. However, the breaking elongation of orthogonal woven structure is independent of weave and number of layers.

Many researchers used kinematic (pin-joint) approach to study deformation behavior of textile fabrics. The acute angle between warp and weft can be used as a measure of deformation caused due to shearing. Before any deformation, this angle for woven fabric is 90°. However, the angle decreases continuously with the increase in deformation until it reaches to critical shearing angle (called as locking angle) just before buckling of fibers. The traditional kinematic model cannot represent the later stages of deformation and locking angle. This model can be used only for single layer and critical experiments are necessary to determine locking angle. To overcome these problems, Prodromou and Chen [22] modified the fabric geometrical parameters, such as tow width and tow spacing, and fiber properties like friction and buckling resistance which determine locking angle. Their study shows that besides geometric modifications in fabric parameters, the factors independent of fabric construction parameters, such as high friction coefficients, inter-ply shear interactions and reduction in global stiffness, may affect wrinkling behavior.

Table 6 Properties of some textile performs [8].

Textile preform	**Advantage**	**Limitation**
Low crimp uniweave	High in-plane properties; good taliorability; highly automated preform fabrication process	Low transverse and out-of-plane properties; poor fabric stability; labor intensive ply lay-up
2-D Woven	Good in-plane properties; good drapability; highly automated perform fabrication process; integrally woven shapes possible; suited for large area coverage and extensive data base	Limited taliorability for off-axis properties ; low out-of-plane properties
3-D Woven	Moderate in-plane and out-of-plane properties; automated preform fabrication process and limited woven shapes are possible	Limited taliorability for off-axis properties and poor drapability
2-D Braid	Good balance in off-axis properties; automated preform fabrication process; well suited for complex curved shapes; good drapability	Size limitation due to machine availability and low out-of-plane properties

3-D Braid	Good balance in in-plane and out-of-plane properties; well suited for complex shapes	Slow preform fabrication process; size limitation due to machine availability
Multi-axial warp knit	Good taliorability for balanced in-plane properties; highly automated preform fabrication process; multi-layer high throughput; material suited for large area coverage	Low out-of-plane properties
Stitched fabrics	Good in-plane properties; highly automated process; provides excellent damage tolerance and out-of-plane strength and excellent assembly aid	Small reduction in in-plane properties; poor accessibility to complex curved shapes

Draping is particularly important in processes like Liquid Composites Molding (LCM) and thermoforming of prepregs. Drape with other preform properties such as wrinkling are also clearly related to bending properties of textile preforms. Formation of complex shaped composites involves bending of preforms in more than one direction and, therefore, the preforms are subjected to form double curvature, which leads shear deformation of preforms. Measurement of fabric buckling is relatively a good method to observe bending rigidity and frictional resistance to bending of fabric. The traditional approach to drape modeling for fabric reinforcements uses a geometric mapping which is based on fabric shear. Long et al. [23] developed a geometrical model which describes shear force and shear strain energy as the function of fabric shear angle. They used warp knitted and woven preforms for the study. They found that the fiber structure has a significant effect on deformation characteristics of fabric. They also developed a mechanical model to determine shearing behavior of woven and warp knitted preforms based on inter-tow friction. The obtained shear properties can be used for draping simulation.

The drape simulation indicates the feasibility of draped form and gives undeformed fabric pattern as well as other important information such as distribution of yarn orientation, fiber volume fraction and thickness of the fabric stack. Wang et al. [24] predicted the draping behavior of preforms by bias extension and simple shear test methods which are based on pin-jointed model. They also studied the effects of aspect ratio and boundary conditions on permeability. They observed considerable differences in preform permeability when different test methods, aspect ratios and boundaries were used. Page and Wang [25] also studied yarn slippage in textile preforms by comparing carbon and glass fabrics and observed higher yarn slippage in carbon fabrics, whereas no such slippage of yarns was observed in glass fabric. The observed yarn slippage was found to be affected by the non-uniformity of deformation, boundary conditions and differences in fabric materials.

Although the various technologies are available for manufacturing composites, only liquid composite molding has the capability of manufacturing polymer composites with large size and complex shapes at low cost. In LCM, a fiber preform, which consists of several layers of dry continuous strand mat, woven roving or cloth, is placed into the mold cavity. The mold is then closed and resin is injected into the cavity to impregnate the preform. Therefore, the permeability of preforms is of prime importance in LCM. Fiber preform permeability is usually dependent on the fiber content, preform structure, binder, arrangement angle of fiber plies, etc. Therefore, the permeability of a given preform is a function of the fiber content only. There are two techniques (parallel flow and radial) for permeability measurements of fiber mats or preform. Han et al.[38] used pressure transducers to measure the permeability of an individual layer in a multi-layered preform. Stoven et al. [26] determined the transfer permeability of planer textile reinforcements such as non-crimped stitched fabric by ultrasound transmission technique. They observed that the sound velocity inside the stack of fibers changes when it gets impregnated and the dry regions of the fiber stack depend on the dimensions of dry regions along the path of acoustic waves.

In the preparation of composites with various LCM techniques, the compaction of textile preforms during tool closure is another important parameter. The yarn bundles in preform get flattened during compaction and, therefore, reduce pores and gaps among fibers and yarns. This results in elastic deformation, inter-layer packing and nesting. As the compressive force increases, the elastic deformation of fabric extends further and the thickness of preform reduces while fiber volume fraction increases. When the force reaches to a certain value, the fabric cannot be further compressed. Chen and Chou [21] developed a 3D compaction model to study the compressive behavior of multi-layer woven preforms in terms of nesting and elastic deformation, which can be used to predict permeability of preform. They found that the compressive force and reduction in preform thickness have empirical relationship and suggested that some further studies are required to understand nonlinear pressure-preform thickness relationship exhibited at the initial stages of experiments.

3.1 Laminated Structures

Composite materials consist of a combination of materials that are mixed together to achieve specific structural properties. The individual materials do not dissolve or merge completely in the composite, but they act together as one. Normally, the components can be physically identified as they interface with one another. The properties of the composite material are superior to the properties of the individual materials from which it is constructed.

An advanced composite material is made of a fibrous material embedded in a resin matrix, generally laminated with fibers oriented in alternating directions to give the material strength and stiffness. Fibrous materials are not new; wood is the most common fibrous structural material known to man [27]. Applications of composites on aircraft include:

- Fairings
- Flight control surfaces
- Landing gear doors
- Leading and trailing edge panels on the wing and stabilizer
- Interior components
- Floor beams and floor boards
- Vertical and horizontal stabilizer primary structure on large aircraft
- Primary wing and fuselage structure on new generation large aircraft
- Turbine engine fan blades
- Propellers

3.1.1 Major Components of a Laminate

An isotropic material has uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing. Metals such as aluminum and titanium are examples of isotropic materials. A fiber is the primary load carrying element of the composite material. 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. Components made from fiber reinforced composites can be designed so that the fiber orientation produces optimum mechanical properties, but they can only approach the true isotropic nature of metals, such as aluminum and titanium.

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 [27].

3.1.2 Strength Characteristics

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 [27].

3.1.3 Fiber Orientation

The strength and stiffness of a composite buildup 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. 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. 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. These types of ply orientation simulate the properties of an isotropic material. Many aerospace composite structures are made of quasi-isotropic materials.

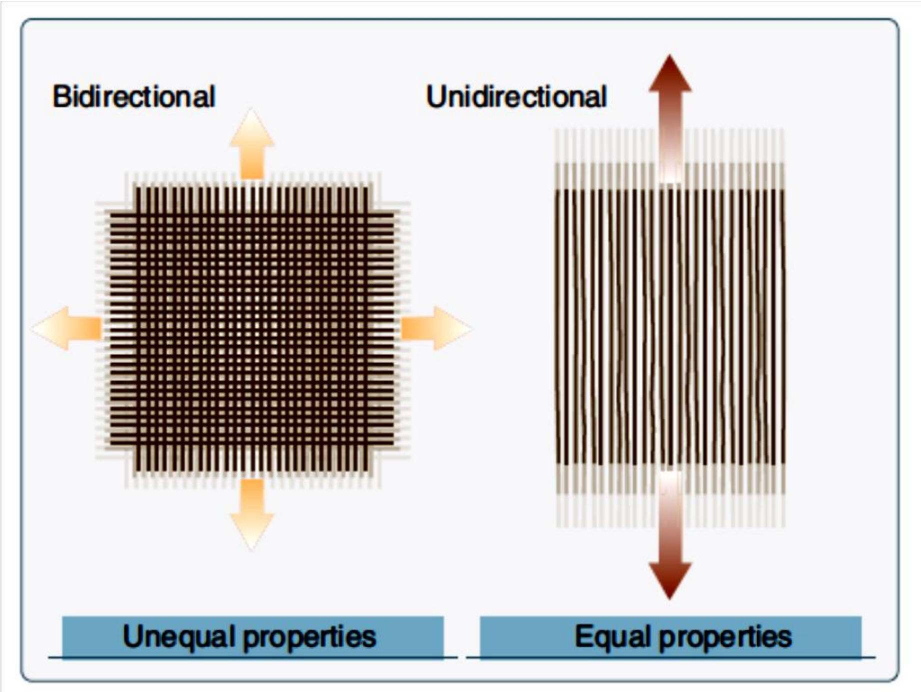

Figure 10 Bidirectional and unidirectional material properties [27].

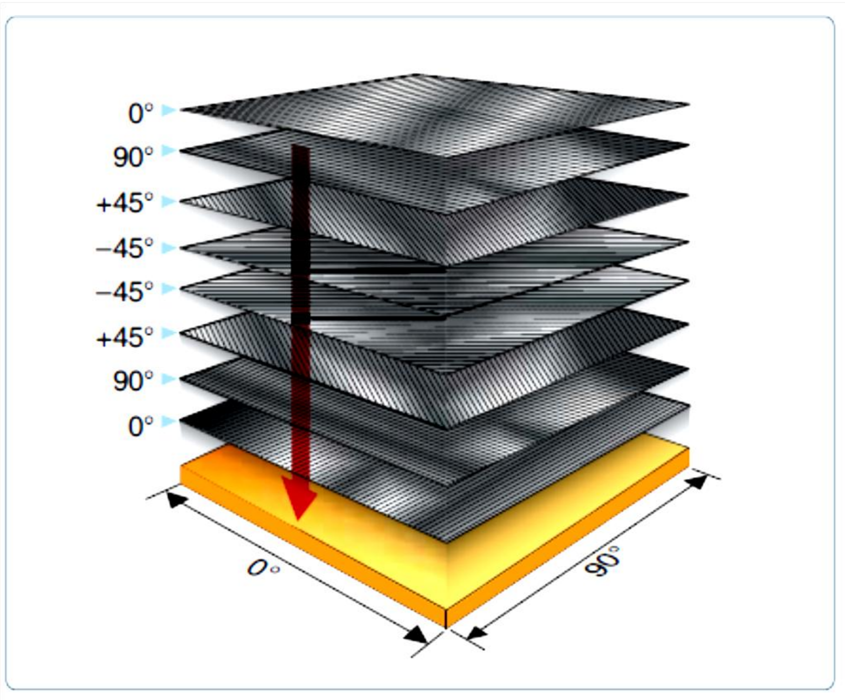

Figure 11 Quasi-isotropic material lay-up [27].

3.1.4 Warp Clock

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 shown in Figure 12.

3.2 Fiber Forms

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 [27].

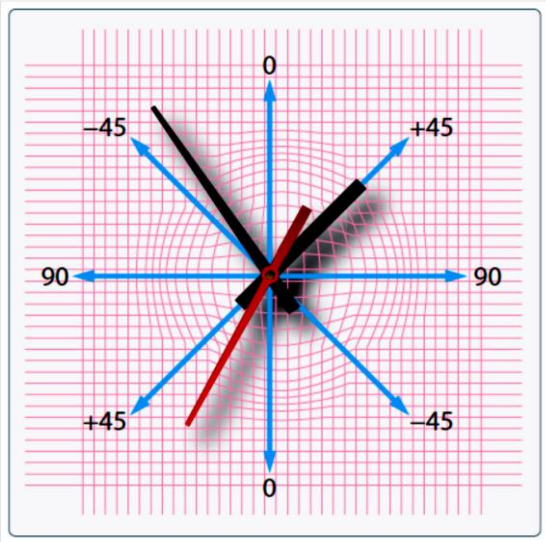

Figure 12 A warp clock [27].

3.2.1 Roving

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, K meaning 1,000 filaments. Most applications for roving products utilize mandrels for filament winding and then resin cure to final configuration.

3.2.2 Unidirectional (Tape)

Unidirectional prepreg tapes have been the standard within the aerospace 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.

3.2.3 Bidirectional (Fabric)

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.

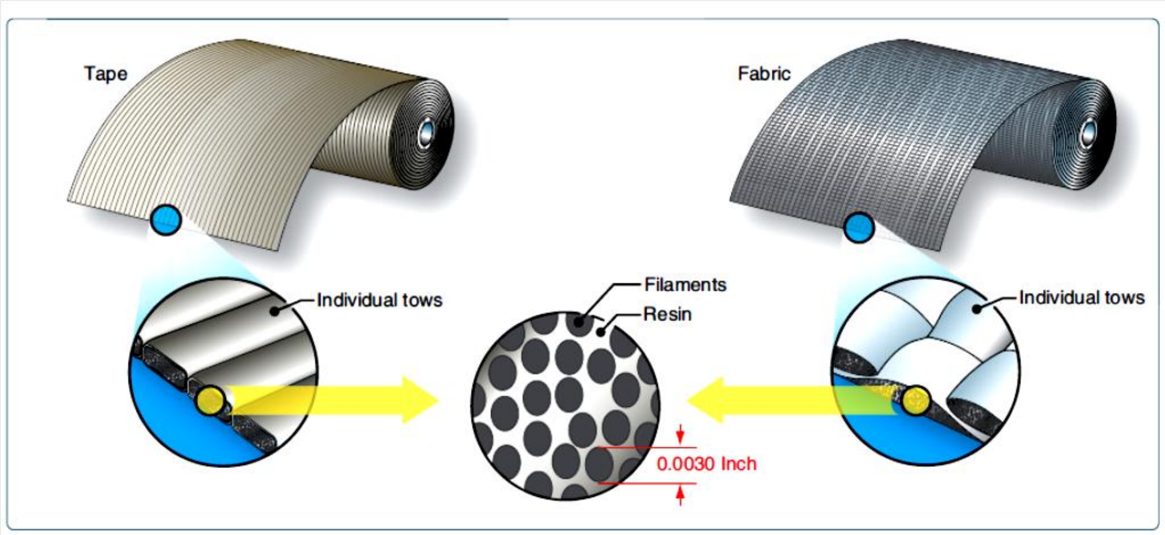

Figure 13 Tape and fabric products [27].

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 [27].

3.2.4 Nonwoven (Knitted or Stitched)

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.

3.3 Types of Fiber

3.3.1 Fiberglass

Fiberglass is often used for secondary structure on aircraft, such as fairings, radomes, and wing tips. Fiberglass is also used for helicopter rotor blades. There are several types of fiberglass used in the aviation industry. Electrical glass, or E-glass, is identified as such for electrical applications. It has high resistance to current flow. E-glass is made from borosilicate glass. S-glass and S2-glass identify structural fiberglass that have a higher strength than E-glass. S-glass is produced from magnesia-alumina-silicate. Advantages of fiberglass are lower cost than other composite materials, chemical or galvanic corrosion resistance, and electrical properties (fiberglass does not conduct electricity). Fiberglass has a white color and is available as a dry fiber fabric or prepreg material.

3.3.2 Kevlar®

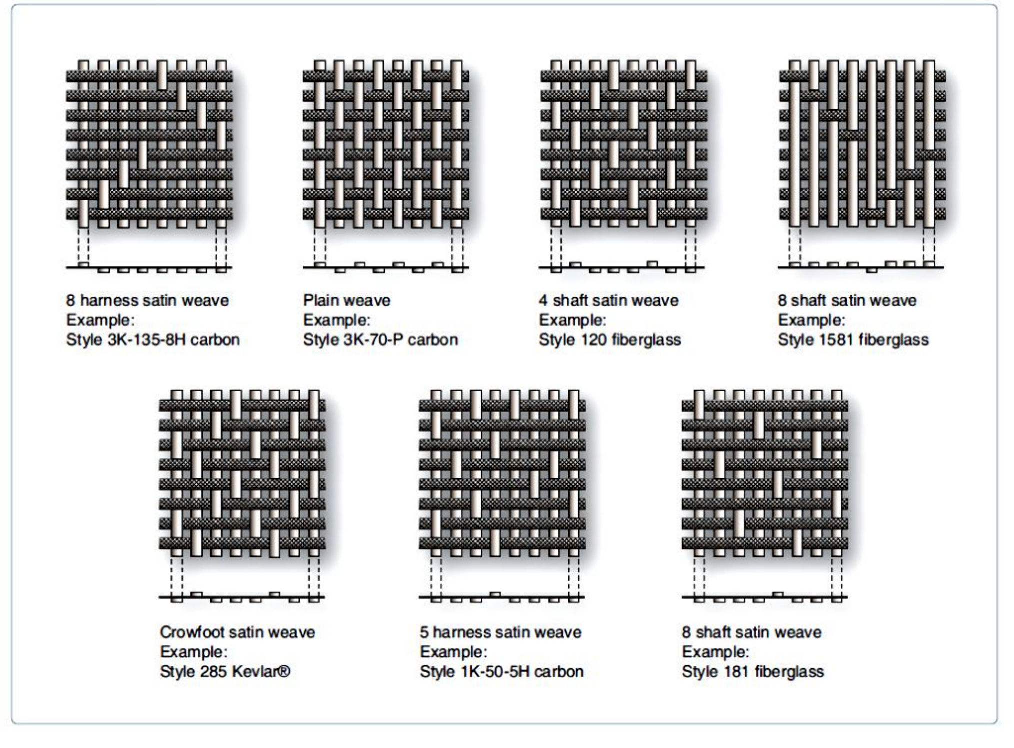

Figure 14 Typical fabric weave styles [27].

Kevlar® is DuPont's name for aramid fibers. Aramid fibers are light weight, strong, and tough. Two types of Aramid fiber are used in the aviation industry. Kevlar® 49 has a high stiffness and Kevlar® 29 has a low stiffness. An advantage of aramid fibers is their high resistance to impact damage, so they are often used in areas prone to impact damage. The main disadvantage of aramid fibers is their general weakness in compression and hygroscopy. Service reports have indicated that some parts made from Kevlar® absorb up to 8 percent of their weight in water. Therefore, parts made from aramid fibers need to be protected from the environment. Another disadvantage is that Kevlar® is difficult to drill and cut. The fibers fuzz easily and special scissors are needed to cut the material.

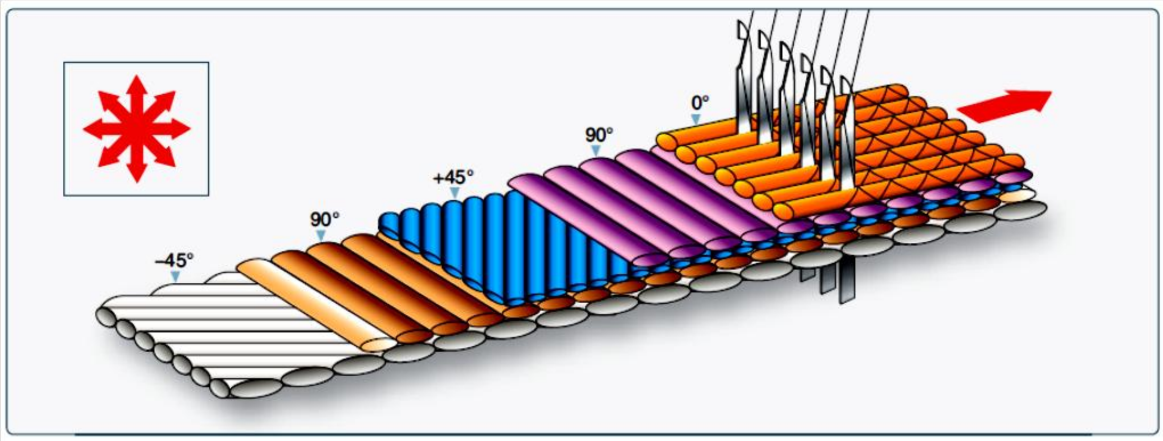

Figure 15 Nonwoven material (stitched) [27].

Kevlar® is often used for military ballistic and body armor applications. It has a natural yellow color and is available as dry fabric and prepreg material. Bundles of aramid fibers are not sized by the number of fibers like carbon or fiberglass but by the weight.

3.3.3 Carbon/Graphite

One of the first distinctions to be made among fibers is the difference between carbon and graphite fibers, although the terms are frequently used interchangeably. Carbon and graphite fibers are based on graphene (hexagonal) layer networks present in carbon. If the graphene layers, or planes, are stacked with three dimensional order, the material is defined as graphite. Usually extended time and temperature processing is required to form this order, making graphite fibers more expensive. Bonding between planes is weak. Disorder frequently occurs such that only two-dimensional ordering within the layers is present. This material is defined as carbon.

Carbon fibers are very stiff and strong, 3 to 10 times stiffer than glass fibers. Carbon fiber is used for structural aircraft applications, such as floor beams, stabilizers, flight controls, and primary fuselage and wing structure. Advantages include its high strength and corrosion resistance. Disadvantages include lower conductivity than aluminum; therefore, a lightning protection mesh or coating is necessary for aircraft parts that are prone to lightning strikes. Another disadvantage of carbon fiber is its high cost. Carbon fiber is gray or black in color and is available as dry fabric and prepreg material. Carbon fibers have a high potential for causing galvanic corrosion when used with metallic fasteners and structures.

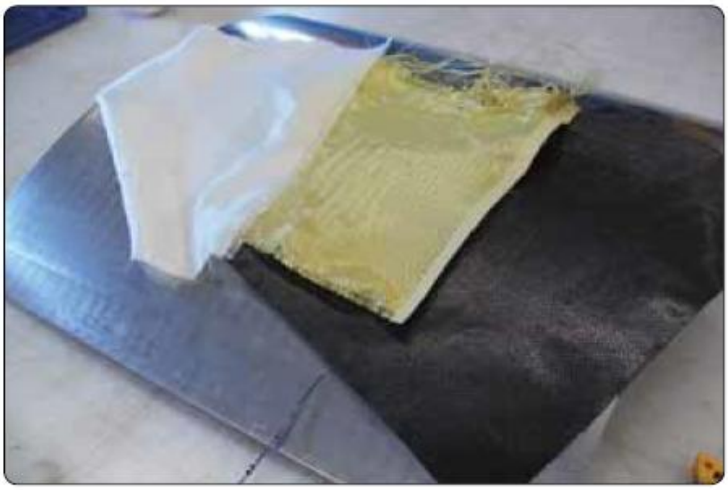

Figure 16 Fiberglass (left), Kevlar (middle), and carbon fiber material (right) [27].

3.3.4 Boron

Boron fibers are very stiff and have a high tensile and compressive strength. The fibers have a relatively large diameter and do not flex well; therefore, they are available only as a prepreg tape product. An epoxy matrix is often used with the boron fiber. Boron fibers are used to repair cracked aluminum aircraft skins, because the thermal expansion of boron is close to aluminum and there is no galvanic corrosion potential. The boron fiber is difficult to use if the parent material surface has a contoured shape. The boron fibers are very expensive and can be hazardous for personnel. Boron fibers are used primarily in military aviation applications.

3.3.5 Ceramic Fibers

Ceramic fibers are used for high-temperature applications, such as turbine blades in a gas turbine engine. The ceramic fibers can be used to temperatures up to 2,200 °F.

3.4 Matrix Materials

3.4.1 Thermosetting Resins

Resin is a generic term used to designate the polymer. The resin, its chemical composition, and physical properties fundamentally affect the processing, fabrication, and ultimate properties of a composite material. Thermosetting resins are the most diverse and widely used of all man-made materials. They are easily poured or formed into any shape, are compatible with most other materials, and cure readily (by heat or catalyst) into an insoluble solid. Thermosetting resins are also excellent adhesives and bonding agents.

3.4.2 Polyester Resins

Polyester resins are relatively inexpensive, fast processing resins used generally for low cost applications. Low smoke producing polyester resins are used for interior parts of the aircraft. Fiber-reinforced polyesters can be processed by many methods. Common processing methods include matched metal molding, wet layup, press (vacuum bag) molding, injection molding, filament winding, pultrusion, and autoclaving.

3.4.3 Vinyl Ester Resin

The appearance, handling properties, and curing characteristics of vinyl ester resins are the same as those of conventional polyester resins. However, the corrosion resistance and mechanical properties of vinyl ester composites are much improved over standard polyester resin composites.

3.4.4 Phenolic Resin

Phenol-formaldehyde resins were first produced commercially in the early 1900s for use in the commercial market. Ureaformaldehyde and melamine-formaldehyde appeared in the 1920–1930s as a less expensive alternative for lower temperature use. Phenolic resins are used for interior components because of their low smoke and flammability characteristics.

3.4.5 Epoxy

Epoxies are polymerizable thermosetting resins and are available in a variety of viscosities from liquid to solid. There are many different types of epoxy, and the technician should use the maintenance manual to select the correct type for a specific repair. Epoxies are used widely in resins for prepreg materials and structural adhesives. The advantages of epoxies are high strength and modulus, low levels of volatiles, excellent adhesion, low shrinkage, good chemical resistance, and ease of processing. Their major disadvantages are brittleness and the reduction of properties in the presence of moisture. The processing or curing of epoxies is slower than polyester resins. Processing techniques include autoclave molding, filament winding, press molding, vacuum bag molding, resin transfer molding, and pultrusion. Curing temperatures vary from room temperature to approximately 350 °F (180 °C). The most common cure temperatures range between 250° and 350 °F (120–180 °C).

3.4.6 Polyimides

Polyimide resins excel in high-temperature environments where their thermal resistance, oxidative stability, low coefficient of thermal expansion, and solvent resistance benefit the design. Their primary uses are circuit boards and hot engine and airframe structures. A polyimide may be either a thermoset resin or a thermoplastic. Polyimides require high cure temperatures, usually in excess of 550 °F (290 °C).

Consequently, normal epoxy composite bagging materials are not usable, and steel tooling becomes a necessity. Polyimide bagging and release films, such as Kapton® are used. It is extremely important that Upilex® replace the lower cost nylon bagging and polytetrafluoroethylene (PTFE) release films common to epoxy composite processing. Fiberglass fabrics must be used for bleeder and breather materials instead of polyester mat materials due to the low melting point of polyester.

3.4.7 Polybenzimidazoles (PBI)

Polybenzimidazole resin is extremely high temperature resistant and is used for high temperature materials. These resins are available as adhesive and fiber.

3.4.8 Bismaleimides (BMI)

Bismaleimide resins have a higher temperature capability and higher toughness than epoxy resins, and they provide excellent performance at ambient and elevated temperatures.

The processing of bismaleimide resins is similar to that for epoxy resins. BMIs are used for aero engines and high temperature components. BMIs are suitable for standard autoclave processing, injection molding, resin transfer molding, and sheet molded compound (SMC) among others.

3.5 Thermoplastic Resins

Thermoplastic materials can be softened repeatedly by an increase of temperature and hardened by a decrease in temperature. Processing speed is the primary advantage of thermoplastic materials. Chemical curing of the material does not take place during processing, and the material can be shaped by molding or extrusion when it is soft.

3.5.1 Semicrystalline Thermoplastics

Semicrystalline thermoplastics possess properties of inherent flame resistance, superior toughness, good mechanical properties at elevated temperatures and after impact, and low moisture absorption. They are used in secondary and primary aircraft structures. Combined with reinforcing fibers, they are available in injection molding compounds, compression-moldable random sheets, unidirectional tapes, prepregs fabricated from tow (towpreg), and woven prepregs. Fibers impregnated in semicrystalline thermoplastics include carbon, nickel-coated carbon, aramid, glass, quartz, and others.

3.5.2 Amorphous Thermoplastics

Amorphous thermoplastics are available in several physical forms, including films, filaments, and powders. Combined with reinforcing fibers, they are also available in injection molding compounds, compressive moldable random sheets, unidirectional tapes, woven prepregs, etc. The fibers used are primarily carbon, aramid, and glass. The specific advantages of amorphous thermoplastics depend upon the polymer. Typically, the resins are noted for their processing ease and speed, high temperature capability, good mechanical properties, excellent toughness and impact strength, and chemical stability. The stability results in unlimited shelf life, eliminating the cold storage requirements of thermoset prepregs.

3.5.3 Polyether Ether Ketone (PEEK)

Polyether ether ketone, better known as PEEK, is a high temperature thermoplastic. This aromatic ketone material offers outstanding thermal and combustion characteristics and resistance to a wide range of solvents and proprietary fluids. PEEK can also be reinforced with glass and carbon.

3.6 Curing Stages of Resins

Thermosetting resins use a chemical reaction to cure. There are three curing stages, which are called A, B, and C.

- A stage: The components of the resin (base material and hardener) have been mixed but the chemical reaction has not started. The resin is in the A stage during a wet layup procedure.

- B stage: The components of the resin have been mixed and the chemical reaction has started. The material has thickened and is tacky. The resins of prepreg materials are in the B stage. To prevent further curing the resin is placed in a freezer at 0 °F. In the frozen state, the resin of the prepreg material stays in the B stage. The curing starts when the material is removed from the freezer and warmed again.
- C stage: The resin is fully cured. Some resins cure at room temperature and others need an elevated temperature cure cycle to fully cure.

3.6.1 Pre-Impregnated Products (Prepregs)

Prepreg material consists of a combination of a matrix and fiber reinforcement. It is available in unidirectional form (one direction of reinforcement) and fabric form (several directions of reinforcement). All five of the major families of matrix resins can be used to impregnate various fiber forms.

The resin is then no longer in a low-viscosity stage, but has been advanced to a B stage level of cure for better handling characteristics. The following products are available in prepreg form: unidirectional tapes, woven fabrics, continuous strand rovings, and chopped mat. Prepreg materials must be stored in a freezer at a temperature below 0 °F to retard the curing process. Prepreg materials are cured with an elevated temperature. Many prepreg materials used in aerospace are impregnated with an epoxy resin and they are cured at either 250 °F or 350 °F. Prepreg materials are cured with an autoclave, oven, or heat blanket. They are typically purchased and stored on a roll in a sealed plastic bag to avoid moisture contamination.

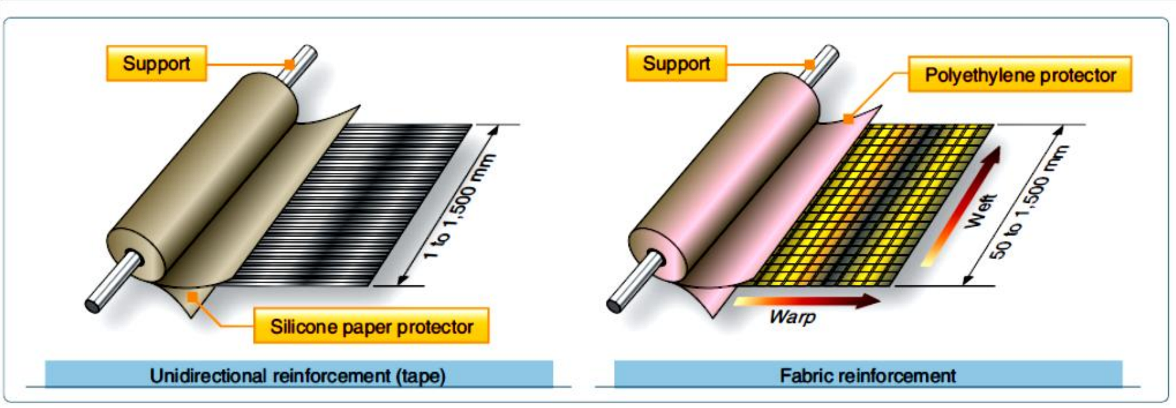

Figure 17 Tape and fabric prepreg materials [27].

3.6.2 Dry Fiber Material

Dry fiber materials, such as carbon, glass, and Kevlar®, are used for many aircraft repair procedures. The dry fabric is impregnated with a resin just before the repair work starts.

This process is often called wet layup. The main advantage of using the wet layup process is that the fiber and resin can be stored for a long time at room temperature. The composite can be cured at room temperature or an elevated temperature cure can be used to speed up the curing process and increase the strength. The disadvantage is that the process is messy and reinforcement properties are less than prepreg material properties.

3.6.3 *Thixotropic Agents*

Thixotropic agents are gel-like at rest but become fluid when agitated. These materials have high static shear strength and low dynamic shear strength at the same time to lose viscosity under stress.

3.7 Adhesives

3.7.1 *Film Adhesives*

Structural adhesives for aerospace applications are generally supplied as thin films supported on a release paper and stored under refrigerated conditions (−18 °C, or 0 °F). Film adhesives are available using high temperature aromatic amine or catalytic curing agents with a wide range of flexibilizing and toughening agents. Rubber-toughened epoxy film adhesives are widely used in aircraft industry. The upper temperature limit of 121–177 °C (250–350 °F) is usually dictated by the degree of toughening required and by the overall choice of resins and curing agents. In general, toughening of a resin results in a lower usable service temperature. Film materials are frequently supported by fibers that serve to improve handling of the films prior to cure, control adhesive flow during bonding, and assist in bond line thickness control. Fibers can be incorporated as short-fiber mats with random orientation or as woven cloth.

Commonly encountered fibers are polyesters, polyamides (nylon), and glass. Adhesives containing woven cloth may have slightly degraded environmental properties because of wicking of water by the fiber. Random mat scrim cloth is not as efficient for controlling film thickness as woven cloth because the unrestricted fibers move during bonding. Spunbonded nonwoven scrims do not move and are, therefore, widely used.

3.7.2 *Paste Adhesives*

Paste adhesives are used as an alternative to film adhesive. These are often used to secondary bond repair patches to damaged parts and also used in places where film adhesive is difficult to apply. Paste adhesives for structural bonding are made mostly from epoxy. One part and two part systems are available. The advantages of paste adhesives are that they can be stored at room temperature and have a long shelf life. The disadvantage is that the bond line thickness is hard to control, which affects the strength of the bond. A scrim cloth can be used to maintain adhesive in the bondline when bonding patches with paste adhesive.

3.7.3 *Foaming Adhesives*

Most foaming adhesives are 0.025-inch to 0.10-inch thick sheets of B staged epoxy. Foam adhesives cure at 250 °F or 350 °F. During the cure cycle, the foaming adhesives expand. Foaming adhesives need to be stored in the freezer just like prepregs, and they have only a limited storage life. Foaming adhesives are used to splice pieces of honeycomb together in a sandwich construction and to bond repair plugs to the existing core during a prepreg repair [27].

3.8 Composite fabrication method

Composite fabrication method in general can be divided into two main processes, namely open and closed moulding. For open mould technique, the top layer of the laminates and matrix are exposed to the atmosphere, resulting in uncontrolled surface condition [6]. Since the tooling fabrication process is relatively simple and low cost, rapid product development cycle is possible to be implemented using this method. The fabrication techniques are summarized in Table 7. The selection of fabrication method depends on several factors such as material, resin system, part complexity and application. Table 8 shows suitability of fabrication method with respect to the production amount.

Table 7 Fabrication method for open and closed mould [1].

Open Mould	Closed Mould
Hand Lay-Up	Vacuum Infusion Processing
Spray-up	Pultrusion
Filament Winding	Resin Transfer Moulding (RTM)
	Compression moulding
	Vacuum Bag Moulding

Table 8 Fabrication method according to volume production [1].

Low Volume	Medium Volume	High Volume
Hand Lay-Up	Filament Winding	Compression Moulding
Vacuum Bagging	Resin Transfer Moulding	Pultrusion
Spray Up	Centrifugal Casting	Continuous Lamination
Vacuum Infusion Processing	Wet Lay Up Compression Moulding	Reinforced Reaction Injection Molding (RRIM)

3.9 Sample fabrication process

The fabrication of a cylinder is described below in order to explain the basics of the automated tape winding process. The manufacturing process is divided in four stages: the preparation, the start, the process and the post-process.

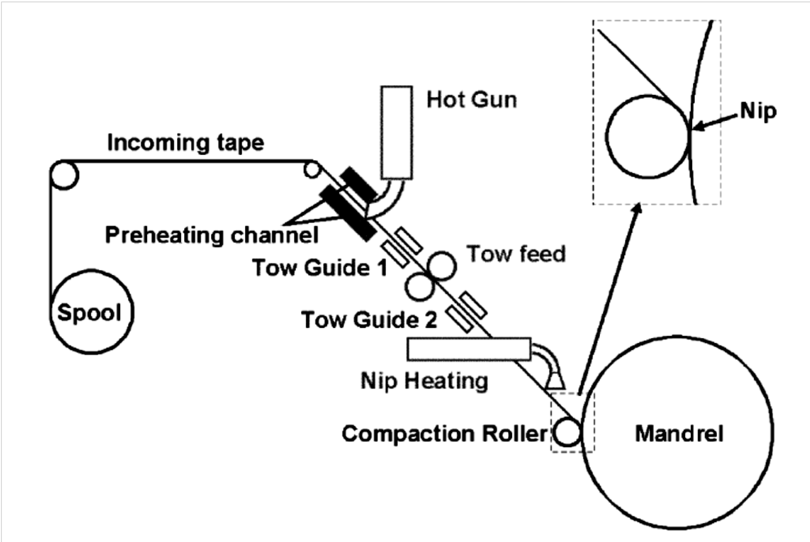

Figure 18 Sketch of an automated tape winding setup at the ETH [1].

The preparation of the setup begins with the mounting of the spool on the spool holder. Then the tape is pulled manually up to the second tow guide (Figure 18). The winding machine is turned on. The motion axes of the winding machine are set. The winding program is loaded. The preheating channel and the nip heating are warmed up.

The start procedure consists to feed the tape (at least up to the nip), to fix the incoming tape on the mandrel, to start the winding program and to apply the compaction force with the compaction roller. During the process, the spool supplies the composite material. The latter is warmed up in the preheating channel and by the nip heating. The incoming tape is compacted with the compaction roller at the nip. It is laid on different paths to fill free volumes. When the laying direction needs to be changed abruptly, the process can be stopped and restarted. The laid material composes the substrate, and its quantity increases as the process is going on. The basic principle of the process is to bond (weld) on-line the incoming tape to the substrate (see sections 2.3.2, 2.3.3 and 2.3.4). The compaction force at the nip enforces the contact between the incoming tape and the substrate. The composite material must be warmed up in order to allow the bonding process. The process is terminated, when the desired quantity of composite material is laid on the planned locations. At this time, the winding program stops automatically. Then the incoming tape is cut and the compaction force is removed. Note that the substrate forms now the cylinder. Generally the cylinder and the mandrel constitute a single part at the end of the process. Therefore, a post-processing stage is necessary. The demolding is the action of separating the mandrel and the cylinder.

3.9.1 The incoming tape

The tapes are composed of fiber material and thermoplastic matrix: e.g. carbon fiber and poly-ether-ether-ketone or glass fiber and polypropylene. The advantages of tapes are that the fibers are pre-impregnated and the matrix pre-consolidated. This means that the fibers and the thermoplastic matrix are bounded, and that the void content is low. This enables to concentrate the research effort on the placement of the tape and the bonding between the substrate and the incoming tape. The latter is described in sections 2.3.2, 2.3.3 and 2.3.4.

The disadvantage of the tapes is that they are expensive. The utilization of more usual preforms (bundles and yarns) permits therefore to reduce the material costs. On the other hand, the fibers need to be impregnated and the thermoplastic matrix consolidated in the bundles and yarns with matrix powder and fibers. The impregnation is the process that describes the evolution of the binding between the fibers and the matrix. The consolidation process depicts the reduction of the void content until the voids vanish.

The impregnation and the consolidation stages must be performed on-line prior to the nip in the automated tape winding and the automated tape placement processes. They necessitates large compaction pressure and large energy inputs to heat the perform material closed to or above the melting temperature of the thermoplastic matrix. The elevated temperature of the matrix is required to facilitate the deformations of the thermoplastic matrix and of the composite material.

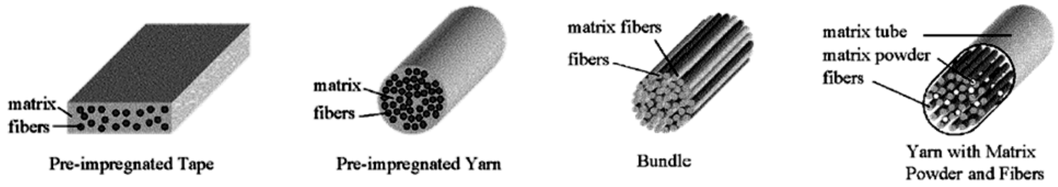

Figure 19 Different types of preforms [1].

3.9.2 The nip point, line or curve

The nip is the location where the incoming tape comes into contact with the support or the substrate. In two-dimensional analysis, it is a point. In three dimensional analysis, the shape of the support (substrate) determines its form. It can be a line or a curve [1].

3.10 Filament winding

Table 9 Characteristics of filament winding process [28].

Resins	Fibres	Advantages	Disadvantages
Matrix epoxy, polyester, polyvinyl ester, phenolic resin	Glass fibre, carbon fibre, aramid fibre, natural plant fibres (the fibres are used straight from a creel and not woven or stitched into a fabric form.)	1. Economic way of laying material down 2. Resin usage can be controlled 3. Minimum fibre cost 4. Good structural properties of laminates	1. Limited to convex shaped components 2. Difficult to lay fibre exactly along the length of component 3. High mandrel cost for large components

Filament winding is mainly used for fabricating open (cylinders) or closed end structures (pressure vessel or tanks) due to high stiffness-to-weight ratios. In a filament winding procedure, the fiber tows are wetted in a resin bath before being wound onto a mandrel in different orientations. The winding process is controlled by fiber feeding mechanism and rate of rotation of the mandrel. The schematic diagram of typical filament winding process. One of the well-known products of filament winding process is composite overwrapped pressure vessels (COPVs), which are vital to spacecraft propulsion, attitude control systems and life support applications. The COPV design requires integration between the analysis of the liner and the fiber overwrap. Ductile materials are usually used as the liners, such as soft aluminum, with only minimal load-sharing capabilities. The fiber is generally applied as ribbon of multiple tows wetted in resin bath. In previous research conducted by Madhavi et al. on design and analysis of filament wound COPV with integrated-end domes, material characterization of FRP of carbon T300/Epoxy for various configurations are determined using filament winding technique. It is found out that having alternate hoop and helical layers with hoop layers as the top and bottom most layers, gave the burst value of 12.4 MPa in the cylindrical zone [28].

3.11 Automated Fiber Placement

Automated tow placement and tape placement are subsets of this method with the differences being in the starting materials and the material laydown rates feasible. The fiber placement process automatically places multiple individual pre-preg tows onto a mandrel at high speed, using a numerically controlled, articulating robotic placement head to dispense, clamp, cut and restart as many as 32 tows simultaneously. Minimum cut length (the shortest tow length a machine can lay down) is the essential ply-shape determinant. The fiber placement heads can be attached to a 5- axis gantry, retrofitted to a filament winder or delivered as a turnkey custom system. Machines are available with dual mandrel stations to increase productivity. Advantages of fiber placement include processing speed, reduced material scrap and labor costs, parts consolidation and improved part-to-part uniformity. Often, the process is used to produce large thermoset parts with complex shapes. Automated tape laying (ATL) is an even speedier automated process in which pre-preg tape, rather than single tows, is laid down continuously to form parts. It is often used for parts with highly complex contours or angles. Tape layup is versatile, allowing breaks in the process and easy direction changes, and it can be adapted for both thermoset and thermoplastic materials. The head includes a spool or spools of tape, a winder, winder guides, a compaction shoe, a position sensor and a tape cutter or slitter. In either case, the head may be located on the end of a multi-axis articulating robot that moves around the tool or mandrel to which material is being applied, or the head may be located on a gantry suspended above the tool. Alternatively, the tool or mandrel can be moved or rotated to provide the head access to different sections of the tool. Tape or fiber is applied to a tool in courses, which consist of one row of material of any length at any angle. Multiple courses are usually applied together over an area or pattern and are defined and controlled by machine-control software that is programmed with numerical input derived from part design and analysis. Capital expenditures for computer-driven, automated equipment can be significant [29].

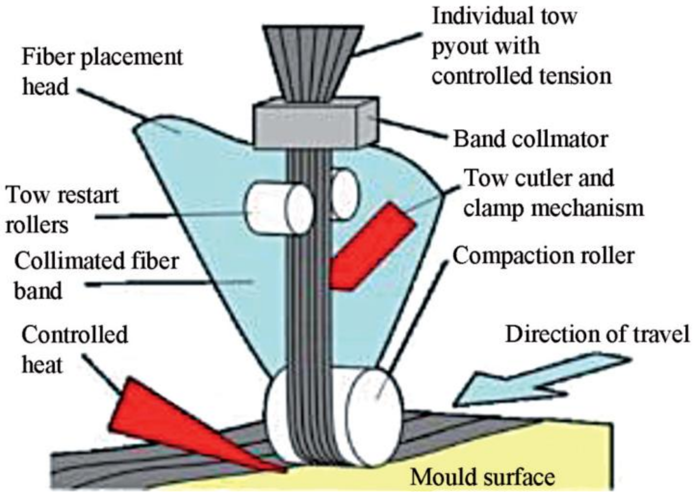

Figure 20 Automatic Fiber Placement head laying pre-preg tape onto the mould [29].

Although ATL generally is faster than AFP and can place more material over longer distances, AFP is better suited to shorter courses and can place material more effectively over contoured surfaces. The latest equipment trend enables both AFP and ATL, switching between the two, in a matter of minutes, by swapping out dock able heads. Another development area is the pursuit of out of autoclave (OOA) in-situ consolidation of high-performance thermoplastic ATL/ATP parts using laser heating and strategically placed mechanical rollers for consolidation. Both methods suffer, however, from the high capital cost of the equipment and facilities required. The payoffs with these methods for automobile applications are in large scale integrated, complex part fabrication where the lower assembly costs due to the reduced part count and reduced tooling fixture requirements can offset the capital costs [29].

3.11.1 Fiber arrangement

Samples were made from two configurations, first a UD arrangement by winding the co-mingled tows around a metal frame, and second from braided cloth made from the co-mingled fiber tows. The Herzog braiding machine at Technical University Munich (RF-128-100) uses a 128 bobbin set-up which can produce a tubular cloth with braiding angles between 30 and 60°. The 22% carbon fiber tows were 2mm in diameter and could be successfully braided at an angle of +45°. Various tubular diameters were braided, the most successful (in terms of good coverage of the mandrel) was 60mm.

Once braided, the tubular cloth was cut to provide layers of cloth for hot compaction trials. The style of braiding was biaxial. The 13% carbon fiber tow was of a smaller diameter (~1mm) and so the maximum diameter that could be braided, without gaps, was slightly lower at 50mm. Figure 20 shows a picture of the braided cloth from the 22% carbon fiber tows and Figure 3b from the 13% carbon fiber tows. In both cases the bottom axis of the picture is 100mm long.

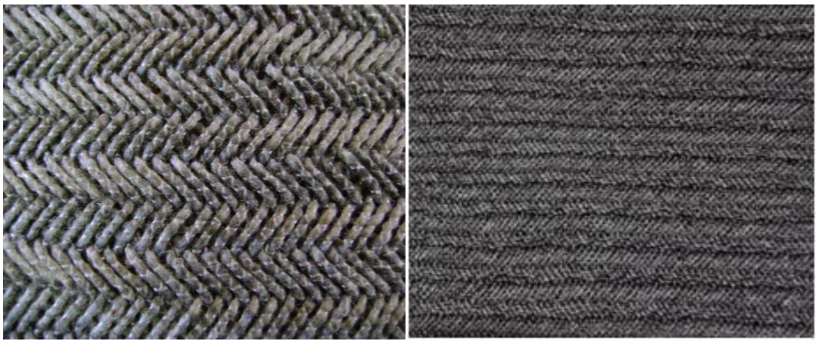

Figure 21 Examples of braided cloth. Left hand side from 22% carbon fiber co-mingled tows, right hand side from 13% carbon fiber co-mingled tows. The bottom axis of both images is equal to 100mm.

4. FUTURE COMPOSITE MANUFACTURING TECHNOLOGY

A major new breakthrough in composites manufacturing technology is not likely to occur in the foreseeable future. Most likely, there will be a series of improvements to existing manufacturing technologies, and manufacturing concepts already generated will be proven. For composites to become competitive with metals, cost reduction has to occur in three areas: nonrecurring costs, recurring costs, and direct operating costs (DOC) (e.g., durability, maintainability, reliability, and repairability). IPD will continue to infiltrate all the disciplines for improved efficiency in design and manufacturing. It is expected that DOC will become a much bigger issue as many aircraft with composite components enter revenue service. There will be doubts as to whether composites will ever become cost-effective for commercial use; however, these doubts can be assuaged by the facts. The reduction in manufacturing cost realized by improved technology will lose its value if it is offset by an increase in nonrecurring costs and DOC. Thus, life cycle cost analyses should be conducted along with the traditional trade-off studies of weight vs. strength and stiffness vs cost. Some of the manufacturing technology developments expected to occur in the foreseeable future is described below.

4.1 Stitched/RTM

Small to medium size stitched/RTM parts have been fabricated with some success; however, the fabrication of complete wing skins and box by this method is a long way off (Note: this method is not cost-effective for small to medium size thin parts; to take full advantage of this method, the parts must be thick and large). For this technology to be incorporated into wing design, an appropriate automatic stitching machine has to be developed. This machine must have the capacity to handle various skin thicknesses, ranging from less than 1/4" to more than 1", and with many different shape and thickness stiffeners attached to it. Concurrently, a new cost-effective resin system specifically for RTM application must be developed. Along with stitched/RTM manufacturing technology, other issues (e.g., repair method, certification, and joints) must be addressed and resolved.

4.2 Filament Winding

This is a mature manufacturing technique which has been in existence for a long time. Improvements in automation, speed, variable thickness, pad-up insertion, consistent quality, flexibility in fiber orientation, control of resin and void content, and shapes other than cylinders will be seen before more versatility appears in application. A combination of robotic and traditional filament winding (with seven to 10-axis) system is already available in crude form. If this system is perfected, it will be able to wind complex non-axisymmetric shapes, such as T and elbow shapes. One of the most critical requirements for a successful implementation of this method is controlling the tension of the deploying filament during the winding processes. This critical problem may be quickly solved with the aid of powerful computers.

4.3 Pultrusion

This method has the potential for cost reduction, but current technology is limited to constant cross sections and is restricted in fiber orientation. Pultrusion is not as popular as metal extrusions. Metal extrusions are attached to other structural members, such as skins and webs, by hundreds and thousands of fasteners and rivets. This method of assembly is not acceptable for composites, where the strong trend is to eliminate fasteners. Consequently, for pultrusion to become an acceptable and popular composites manufacturing technology, it must be possible to pultrude complex multi-element cross sections, such as J-stiffened panels and constant airfoil sections. It is expected that a new technique for making tapered sections with variable thickness and even variable shapes will be available within this decade; significant progress has already been made toward that end in the last few years. Another new development is curved pultrusion. Preforming and braided pultrusion are variations of pultrusion for special applications. New developments can be expected in these areas.

4.4 Continuous Sandwich Panel

This method is already used in production. However, it is limited to making flat constant sandwich panels. Future improvements will increase speed of fabrication and quality. Floor panels, galleys, and partitions are the major uses of flat sandwich panels. Therefore, there is no need for a technology which produces a continuous sandwich panel of complex shapes and variable thickness.

4.5 3-D Weaving

The advantages of 3-D weaving are widely known, but the cost has been prohibitively high. A few automated and semi-automated systems have been created or are under development to reduce cost. Although 3-D weaving is still in its infancy, it has the potential to replace expensive titanium fittings, hinges, engine blades, etc. In addition to reduced costs of weaving, improvements in curing will be seen.

4.6 Mechatronics

Aircraft components in general and composite parts in particular have been known as hand-made custom products as opposed to automotive and electronic products. Full automation is probably not cost-effective for aircraft applications because of relatively low production rates. However, a semi-automated method using mechatronics may be a viable option for aircraft manufacturing. Currently, mechatronics is not a fully developed manufacturing technology, but its development should be followed with keen interest.

4.7 Automatic Tape Layup Machine

Significant progress has been observed in ATL technology. Both speed and accuracy have increased tremendously when compared to early ATL. Advancements in computer technology (hardware and software) have influenced ATL. Along with improvements in speed and accuracy, the capability in size of layup area has also increased. Although a new breakthrough is not expected to occur in ATL technology, improvements will be incremental but continuous.

4.8 Automatic Ply Cutting Machine

This technology has made significant progress in recent years. Three different methods of cutting are used for an APC machine: mechanical, laser, and water. Each has its own advantages and disadvantages. No new breakthroughs are expected in APC technology.

4.9 Tow Placement

Tow placement is relatively new and has received considerable attention in recent years. It combines the advantages of ATL and filament winding. Tow placement can fabricate complex-shaped structures without limitations on fiber angles. It has the potential to reduce production costs significantly. Under the Air Force MANTECH and NASA ACT programs, this technology has proven its worth; however, its use at high production rates still remains to be seen. Future developments include optimized control systems, head position feedback, and in-process inspection for fast, accurate and high quality parts production.

4.10 Co-Curing Technology

The advantages of co-curing technology are numerous, but complex tooling, high risk, and the difficulty of adapting it to high production rates inhibit widespread usage. Continuous improvements in prepreg materials, tooling concepts, quick turnaround, and quality consistency may result in the elimination of those hurdles.

4.11 Forming, Stamping, Injection Molding, Rolling

These manufacturing methods have great potential for high volume production applications, especially when combined with the use of thermoplastics. Application is limited to small to medium size parts. Sporting goods and industrial products will benefit from this group of technologies.

4.12 Repair Technology

Repair technology is gaining more attention. Operators of aircraft are discovering that composites are showing a better service record than are metals, mainly due to their better fatigue and corrosion resistance properties. But at the same time composites are more prone to impact damages, which increase the importance of repair. As new generations of aircraft with tremendous amounts of composites enter flight service, both commercial and military operators will demand improved repair technology. Both the cost of repairs and the down-time resulting from the complexity and special facility and equipment requirements are putting severe demands on repair technology. Current repair technology is not satisfactory, and improvements are necessary.

4.13 Material Technology

Several years ago, the most popular topic in material technology was the "tough resin" system, followed by "thermoplastics." Today's popular materials are "stitched preforms," "tow placement," and "woven textile." Contrary to the original belief that thermoplastics greatly reduce manufacturing cost and time, the observation is now being made that thermoplastic parts cost more and are difficult to produce. In fact, some of the material suppliers are considering discontinuing thermoplastic production. It is still early to predict whether stitched preforms, tow placement, and textile will replace prepregs by the end of this decade. The next three years will be crucial for these so-called new advanced material systems to become dominant. It all depends upon how well these new materials can be adapted to a production mode where cost, quality and manufacturability play important roles.

Operating temperatures of the High Speed Civil Transport will be 250øF to 450øF, depending upon the location of the structure within the aircraft. Epoxy systems alone cannot handle this temperature range. The race for a new material system has already begun, and it is still too early to predict what will happen in an intensely competitive market. Candidate materials are polyimides, bismaleimides, metal matrix, ceramic matrix, etc [1].

Among the several manufacturing processes investigated in the past in the composite laboratory, the automated tape winding with on-line bonding is very promising. In comparison with the other techniques, it has a large potential in terms of economical attractiveness and implementation of tailored design solutions in the finished parts. Due to its high level of automation, the labor work is extremely reduced, the precision of the fiber orientation is high, and the reproducibility and the security during the process are enhanced. The automated tape winding process is very promising, but also very challenging. As tape bonding takes place during tape lay-up, the available process window is small. Since transient conditions exist during the automated tape winding process, the small process window is changing. When the process parameters are not adapted to the variations of the process conditions, the laminate respectively part quality will be affected. In order to fabricate lightweight products, the laminate quality must be maximized. For the automated tape winding process, the intralaminar quality is mainly dependent on the quality of the incoming tape. Therefore the main sensible properties depending on the process are the interlaminar bond properties. This signifies that the interlaminar bond properties must be optimized for the entire laminate with appropriate transient process conditions.

The range of application of a process technique is related to the complexity of the parts that can be produced. During the placement of tapes on complex paths and/or geometries, the form of the nip varies rapidly. In order to bond correctly the tape to the substrate, the compaction system(s) must press the tape on its entire width for all the nip geometries [1]. The use of carbon fiber-reinforced composites has been growing exponentially in the past few decades. They offer excellent mechanical properties in combination with a low density, making them an ideal solution for many lightweight applications. However, they often suffer from a lack of toughness. In contrast with carbon fiber composites, self-reinforced (or all-polymer) composites have an excellent toughness, but a relatively low stiffness and strength. They consist of an oriented polymer fiber or tape in a matrix made from the same polymer. The present invention aims to break through the typical stiffness-toughness dilemma by hybridizing carbon fibers with self-reinforced polypropylene (SRPP) to design a material that has some optimum combination of stiffness and toughness [30].

Increasing global awareness on the environmental sustainability has led to numerous developments on renewable materials such as natural fibers in the fabrication of composite parts. A hybrid composite, which is a combination of two or more materials in a common matrix, has been implemented since natural fiber composites do not have adequate strength to substitute conventional synthetic fiber. By having hybrid composites, the advantages of one type of fiber could complement what is lacking in the other, resulting in a balance in performance and cost through proper material design [3]. The mechanical properties of natural fiber reinforced composite (NFRC) such as stiffness, strength and moisture resistant behavior are also significantly improved by incorporation of stronger and more corrosion-resistant synthetic fiber such as glass or carbon fiber. A study by M. Ramesh et al. [31] indicated that hybridization of glass fiber into sisal/jute reinforced epoxy composites showed good tensile strength of 68.55MPa. Another study by M. Thwe et al. [32] depicted that incorporation of glass fiber up to 20% by mass with bamboo fiber increased tensile and flexural modulus by 12.5% and 10%, respectively. Sanjay et al. [33] investigated flammability behavior and degradation of PP/banana and glass fiber-based hybrid composites and found out that hybridization with glass improved flame retardant characteristic. T. Subash et al. [34] discussed about bast fibers reinforced hybrid composites for aircraft indoor structures applications. These materials provide the benefits in the making of the body panels such as in seat cushions, cabin linings, parcel shelves and many more. The natural fibers such as jute, kenaf, bagasse, bamboo, coir, sisal proved that these materials have a greater strength in aerospace and automotive industry. These composites show lower density as compared to metal composites and have a higher potential to make lightweight sustainable finished parts that can reduce tremendous amount of energy consumption in the industry. There are various fabrication methods applicable for producing bio-sourced composites for usage in aerospace and automotive applications.

Hybridization of SRPP with carbon fibers resulted in a novel class of hybrid composites with a unique combination of stiffness, strength, ultimate failure strain and impact resistance. The key to the invention is to develop suitable strategies to maintain the toughness of the SRPP at the point when the carbon fibers fail. A key parameter in achieving this, is the bonding between both components. For strong bonding, the energy released by carbon fiber failure can create damage in the SRPP fraction, causing a decrease in the ultimate failure strain and hence toughness. For weak bonding, the hybrid composite can immediately delaminate over its entire length. The key is therefore to find the optimal level of bonding, thereby controlling the damage development while providing good stiffness and strength.

A second key parameter is related to the distribution of the fibers in the hybrid composites. The carbon fibers should be distributed in the hybrid composites instead of grouped together in thick layers. Three strategies are proposed: thin layers (layer level), coweaving (intralayer level) and co-mingling (fiber level).

The final parameter is the fiber volume fraction of the carbon fibers. At high fractions, the energy released by the carbon fibers can damage the SRPP. At an optimal fraction however, the ductility and impact resistance of SRPP can be maintained, while still achieving a substantial increase in stiffness and strength over a pure SRPP.

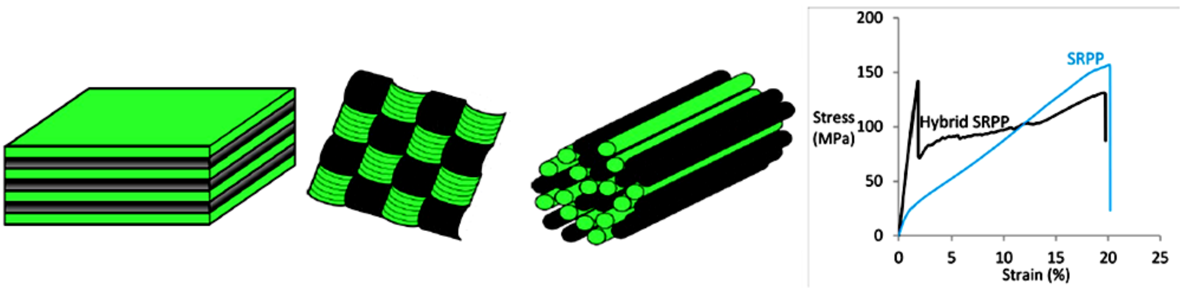

Figure 22 Stress – Strain curve of SRPP [30].

The developed hybrid SRCs possess a unique combination of stiffness, strength and toughness. Since hybrid SRCs can be thermoformed, their products can be manufactured in high volumes. This material therefore has a strong potential to be used in the automotive industry [30].

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