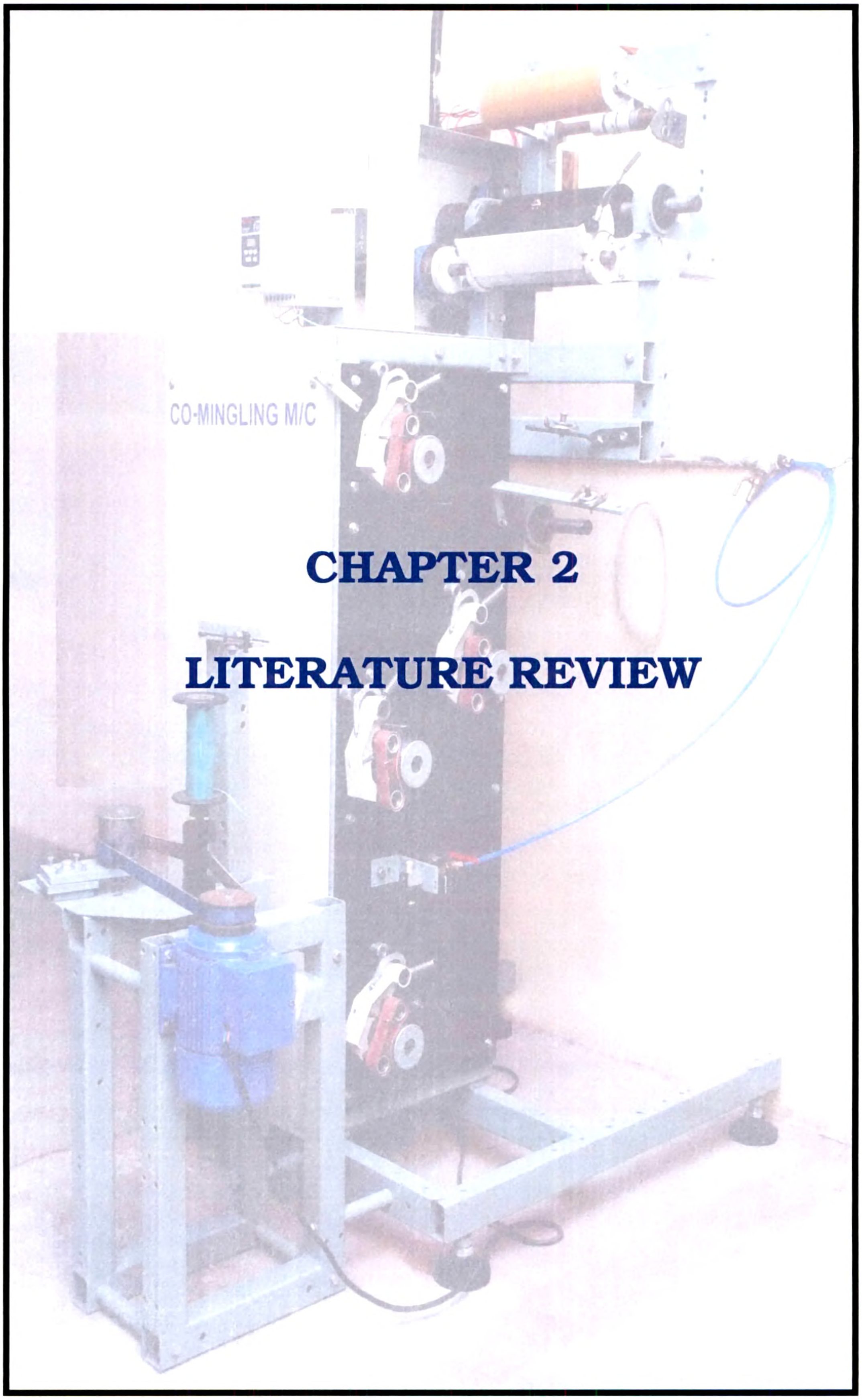
# CHAPTER 2

# LITERATURE REVIEW



# CHAPTER 2 LITERATURE REVIEW

## Hybrid Yarn for Thermoplastic Composites

## 2.1 INTRODUCTION

**"Engineered Material"** pertaining to textiles is a general term, which encompasses a range of materials that can be designed considering the technical functional requirements for the specific use other than just covering the body or looking fashionable. For the technical performance of various types of textile composites, the different types of fibres, yarns and fabrics may be engineered to meet specific requirements depending on its applications. The recent development in the area of these textile composites have indicated an increasing interest in new drapeable preforms using thermoplastic matrix filament and reinforced filament. These filaments are prepared into yarns using new yarn manufacturing technologies. It allows the material scientists to meet new challenges by extending this technology to other materials also for the advanced engineering structures. At present, relatively little information exists about the engineered yarns used in manufacturing of textile composites. There is also an increasing demand for development of new materials and know-how of processing technology for these materials.

The hybrid yarns with thermoplastic matrix filament and reinforced filament are having high strength, high temp resistance, soft and drapeable material for textile preforms[1]. New types of glass/polypropylene hybrid yarns have been produced as part of this work using two different techniques on a single machine. The effect of processing parameters on commingling behaviour and properties of glass/polypropylene commingled hybrid yarn are studied.

## 2.2 MARKET FOR TEXTILE COMPOSITES

The textile composites are structural products made by commingling different polymeric materials used in various industrial applications. In India the technical activities on advanced composites are quite new. The different technical textiles, mainly used for the manufacturing of composites, are the major concern for the glass and textile industry.

According to the market survey carried out by D. Rigby[4] and Associates, the use of technical textiles in textile composites accounted for about 15% of the entire technical textile market by weight and 10% by value. The trend for world consumption of technical textiles for composites, during the period 1985 to 2005 shows that the growth rate is extremely positive (+9.5% per year) which is higher than the growth rate of over all technical textiles (+6.3% per year) in general (Fig. 2.1).

The thermoplastic materials are considerably used as matrix system for the advance composites. Unlike glass and carbon reinforcement, very little work has been reported, inspite of very good market of thermoplastic materials[2]. Fig. 2.2 shows that from various reinforced materials the glass (43%) and carbon(27%) occupies the major market shares in textile composites[3]. The fibres used for reinforcement in composite are mainly glass because carbon

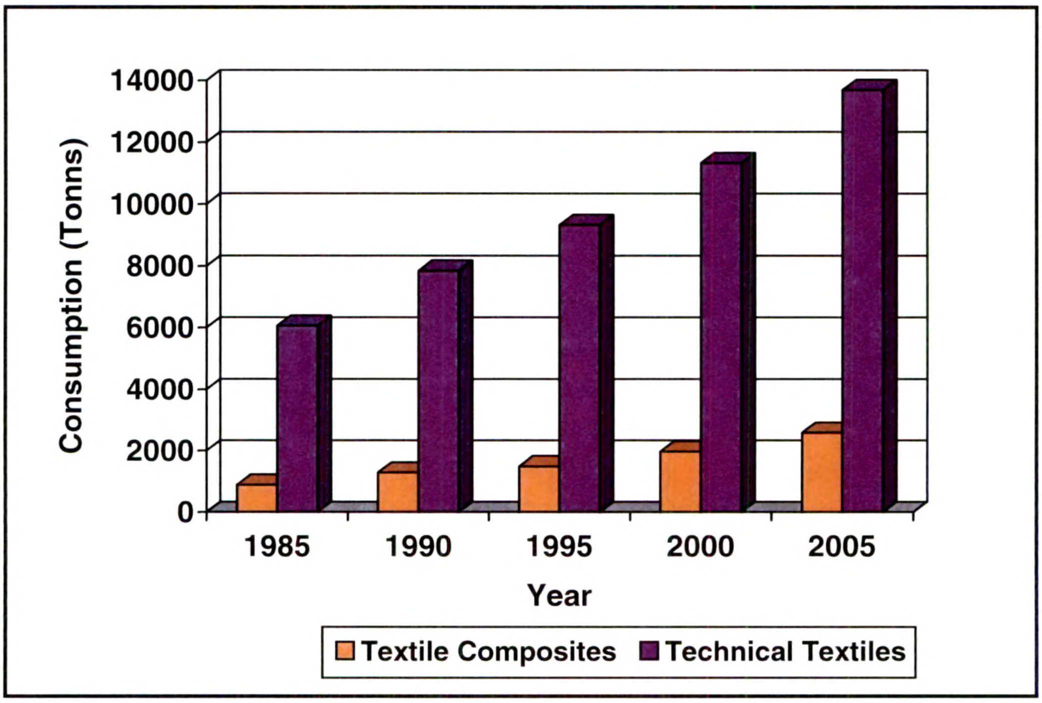



Fig. 2.1 World consumption of technical textiles for textile composites

fibres has an average cost of $55.00 per Kg as opposed to $1.80 - $1.90 per kg for glass fibre. The cost of aramide is also about $30.00 per kg. In the year 1995, a total of 2,300,000 tones of glass fibres were consumed, at a cost of $ 4.3 billion, out of which 1,500,000 tones of reinforcement were consumed at the cost of $2.9 billion.

In India, out of 20 years of activities on textile reinforced composites, in the beginning, main emphasis was laid on the research and development of the composites. Number of organizations and institutes were engaged in various studies pertaining to both reinforcing component and matrix component of these composites. Most of the efforts were being made by government organizations including academic institutions(Fig. 2.3). The break up of activities shows that priority is being given in the area of testing and development of reinforcement of composites (Fig. 2.4).

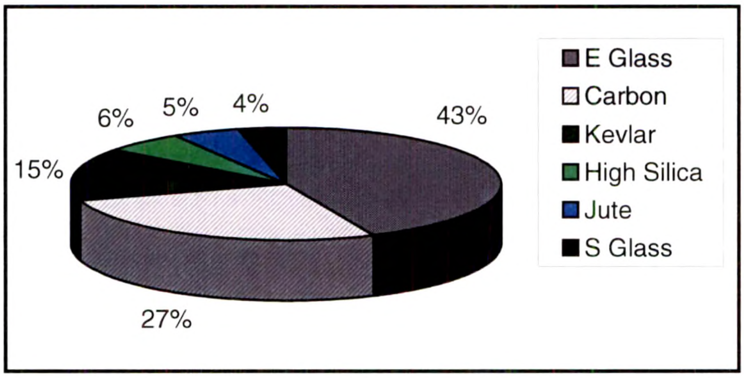



Fig. 2.2 Proportion of various textile reinforcement materials for composite (Year 2004-2005)

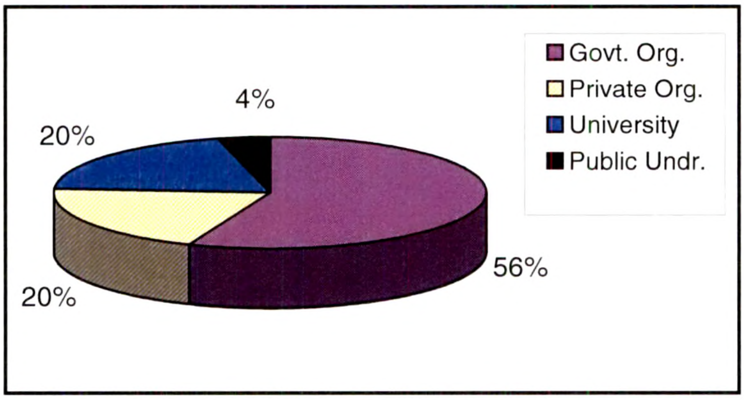



Fig. 2.3 0rganizations involved in the activities of reinforcement (Year 2004-2005)

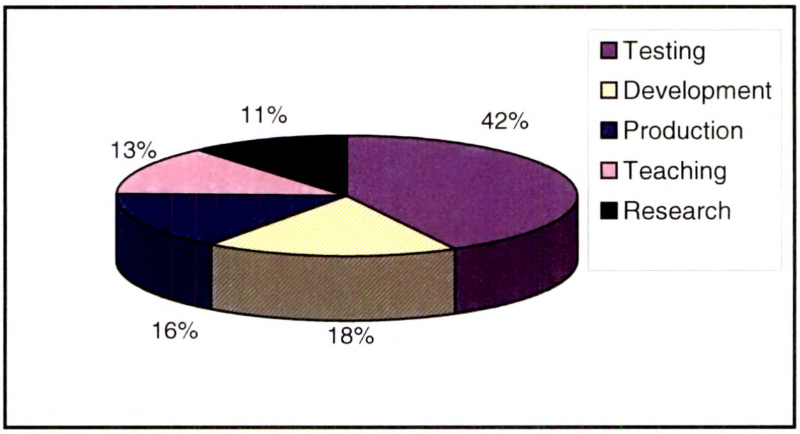



Fig. 2.4 Break up of activities on reinforcement
(Year 2004-2005)

Fig. 2.5 shows the break up of the Indian organizations involved in various activities in the matrix systems. The government organizations as well as some private sectors have taken leading part in the activities on matrix. In case of matrix, the private sectors contribute substantially better than that of reinforcement. Fig. 2.6 shows that the most of the organizations were involved in research and development production of the composite.

The global market for continuous fibre reinforced thermoplastic composites has experienced exceptional rise in recent years with increase in growth rate from 90% to 105% in the last 5 years. According to E-Composites Inc[4]; a Michigan based market research and businesses consulting firm the continuous fibre reinforced thermoplastic composites include a variety of products viz. unidirectional and fabric prepregs, narrow tapes, commingled

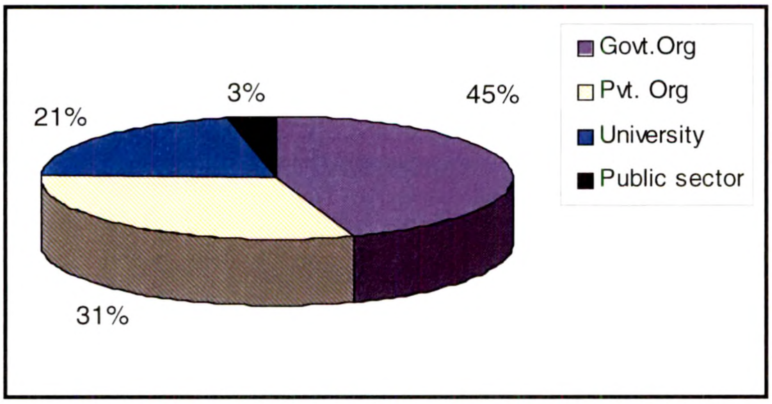



Fig. 2.5 0rganization involved in activities of matrix materials
(Year 2004-2005)

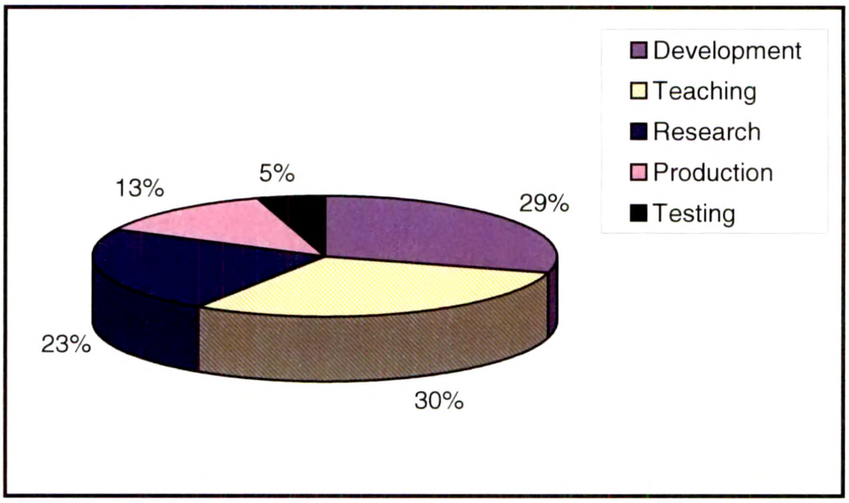



Fig. 2.6 Break up of activities on matrix materials
(Year 2004-2005)

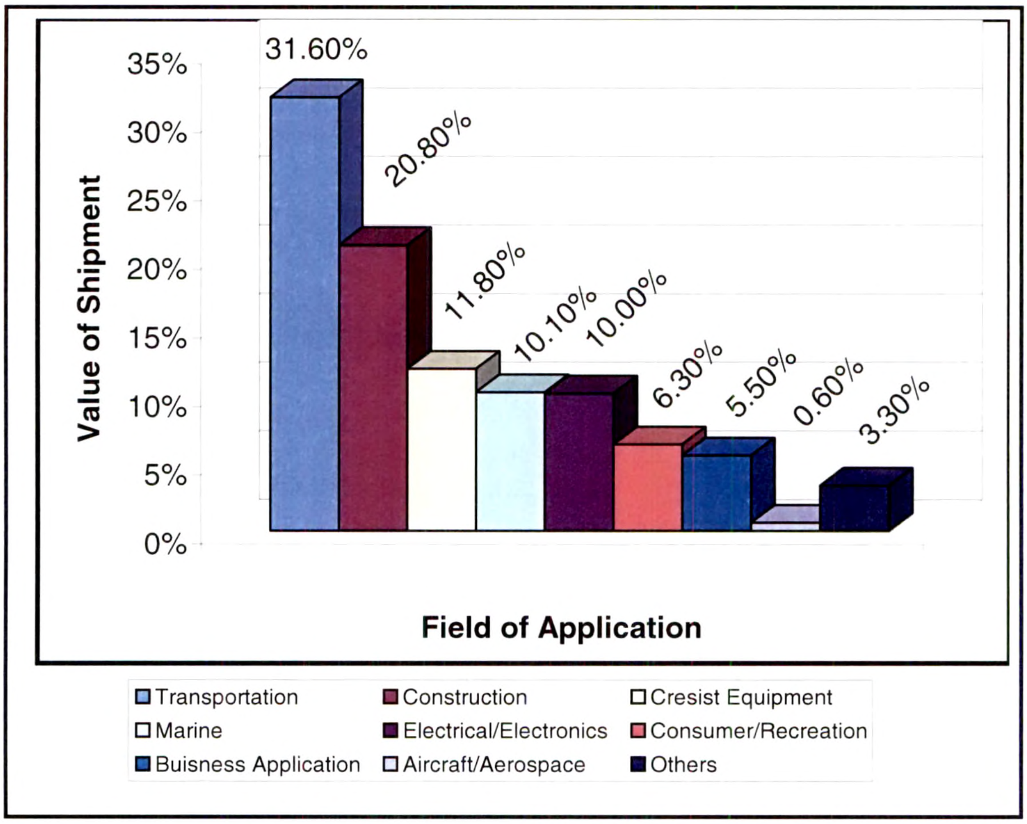



Fig. 2.7 Distribution of end use applications of textile composites
(Year 2005)

fibre in roving and fabric forms, sheets and rods. Common reinforcement materials used in the thermoplastic composites are E-glass, carbon and aramid. Resins typically selected are polypropylene (PP), Nylon, PPS, PEEK, PC and PEI. Historically, these composite materials were used in niche applications such as in aerospace and defence field. But in recent years, the composites are increasingly used in automotive, sporting, transportation, industrial and other applications. Demand has been driven by a variety of aerospace, automotive, industrial and construction applications as shown in Fig. 2.7. However, continuous fibre reinforced thermoplastic composites are even finding their way into furniture, fastener, medical, marine, and other such applications.

The market for fabricators/end-users of continuous fibre reinforced thermoplastics composites is crowded with smaller and emerging producers to large corporations such as Airbus, Boeing and Peguform. Main suppliers of thermoplastic composites are based at North America and Europe including company viz. Cytec, Saint Gobain and Hexcel. In the worldwide continuous fibre reinforced thermoplastic composites market, North America plays an important role with more than 2/3 share, whereas Europe is ranked second largest with about 30%.

The market study[3], 2003-2008 assesses the current and forecast market for almost all types of material forms such as prepregs, commingled fibre in roving and fabric forms, sheets and rods. The thermoplastic composites market is classified on the basis of type of material forms, (prepregs, commingled fibres, etc.), resins, reinforcements, by region and as per applications. The study also profiles molders and leading producers of thermoplastic composites. US based E-Composites Inc. has been tracking the composites industry for many years and has customers ranging from small to multi-national companies such as AOC, Conoco, Dow Chemical, Dow Corning, GE, General Motors, Hexcel, Johns Manville, Lockheed Martin, Owens Corning, Saint Gobain etc[4].

## 2.3 TEXTILE FLEXIBLE COMPOSITE

The technology for combining material into high performance composite is uncommon in the textile industry, but is commonly practiced by manufacturers specializing in high strength to weight ratio materials for application such as automotive and aerospace industry[5]. A composite laminates of relatively light to medium weight comprised of hot melt from thermoplastic material and the fabric prefoms of reinforced material. The thermoplastic material covers and binds reinforced material about 15% to 75% but does not penetrate a substantial amount into yarn structure, which gives flexibility to laminates[6]. This flexible thermoplastic composite sheet offer a number of potential advantages, such as high modulus and specific strength, compared with traditional materials. The previous dominance of thermosetting resins as matrix material is currently being challenged by thermoplastics, because of their potential for low-cost, mass production and short-time processing methods[12].

### 2.3.1 Manufacturing of Thermoplastic Composite

The thermoplastic has to be melted, intimately mixed with the fibres and formed into the final shape. However, the development of thermoplastic composites has been restricted due to the greater difficulty of this fibre impregnations with thermoplastic melt due to higher viscosity of thermoplastic melt in the range of 10-100Pa.s as compared to 0.2-2.0Pa.s for thermoset resins[6]. Fig. 2.8 shows the outline of conventional and new process of manufacture of there composites.

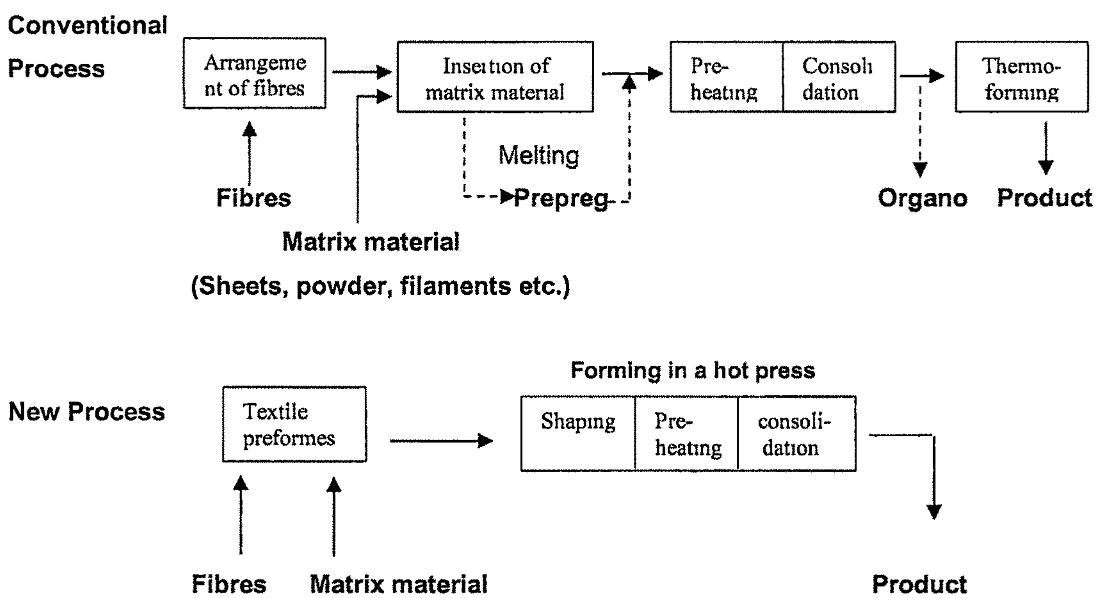



Fig. 2.8 Conventional process and New process of composite manufacture

The manufacturing process of composites mainly comprises of first combining and laying together matrix material and reinforcing element in proper structural arrangement followed by consolidation and solidification of matrix-reinforcing material assemble into new product form.

*a) Combinations of reinforce material with matrix material:*

The various types of polymeric matrix materials and reinforcing materials in different forms are combined using some of the following techniques[11].

- *Commingled fibre*: Continuous fibres of glass or carbon reinforce material commingled with continues filament or polymers.
- *Prepregs*: Reinforcement fibre impregnated with a polymer matrix in the form of thin sheets.
- *Powder impregnated tows*: Continuous tows of fibres impregnated with thermoplastic powder giving a flexible ribbon or sheet.
- *Fibre impregnated thermoplastic*: Powder impregnated continuous fibre encased in a polymer sheath.
- *Short and long fibre reinforced polymer pellets*: Compounded for subsequent extrusion or injection moulding.

b) *Consolidation of reinforcing element and matrix materials*:

The main advantages of thermoplastic composites are[7]:

- Light weight product as compared to steel products
- High structure to mass ratio
- Better corrosion and crack resistance
- Short cycle time allows low capital investment
- Flow process permits high design flexibility
- Potential to automate the process
- High impact strength
- Ability to mould in inserts
- The fibre volume faction can be varied to a wider range

## 2.4 TEXTILE PREFORMS

Textile preform is a structural fibre product made by utilizing textiles processes prior to the formation of composite structures. Textile preforms are the structural backbone of a composite, analogous to the structural steel framework in a RCC-building. The linear assemblies of fibres in continuous and/or discrete form can be organized into the required(1D, 2D or 3D) dimensional structures by means of any of the various textile processes viz. twisting, interlacing, intertwining or interlooping. By proper selection of the geometry of the fibrous structures, architecture and the method of placement or geometric arrangement of the fibres, the structural performance of the composite can be tailored[8].

As shown in Fig. 2.9, textile preform provides a link between raw material systems and the composite product, depending upon the textile performing method used. The range of fibre orientation and fibre volume fraction of the preform and type of fiber orientation affects the matrix infiltration, consolidation and the translation efficiency of fibre properties to the composite product (Fig. 2.9).

The main goal of manufacturing composite structure is to meet design requirements including performance and cost. Textile fabrics are superior to conventional unidirectional prepregs in terms of ease of handling, ability to form around certain complex shapes and forming damage-tolerant composite

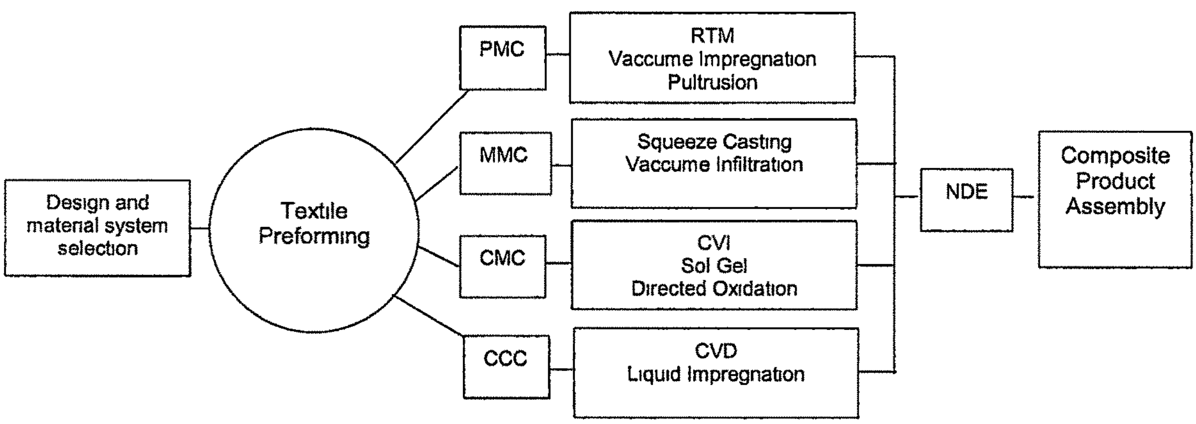



Fig. 2.9 Role of preforms in composite processing[5]

structures. In addition, fabrics are highly compatible with low-cost manufacturing techniques such as compression moulding processes. These low-cost manufacturing techniques are instrumental to the growth of composites in non-aerospace markets. Recently[7] numbers of aerospace companies are also investing in liquid moulding techniques and investigating "textile preforms" as reinforcement. NASA, through advanced composites technology program, evaluated the feasibility of textile composites for the aerospace application.

### 2.4.1 Classification of Preforms

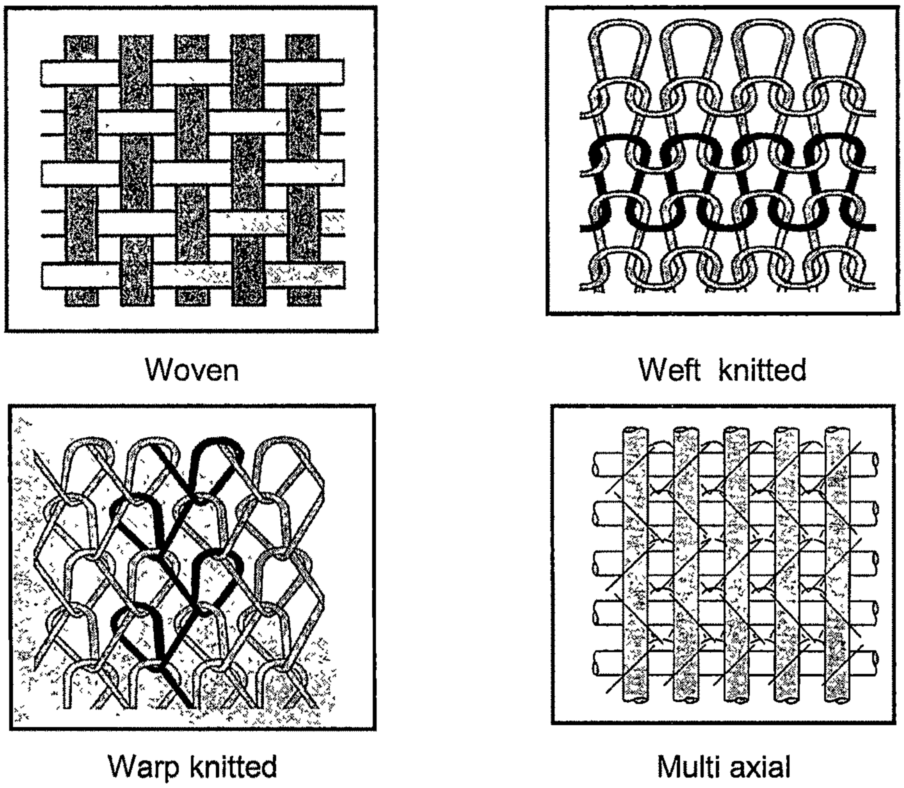
Developments in the field of preforms has led to the production of preforms with assemblies of fibres orientated in different directions, with weaving, knitting and nonwoven, individually or combined[9]. Table 2.1 shows different preforming techniques with respect to yarn direction and fabric forming principles. The different types of preform structure along with preforms are shown in Fig. 2.10.

Table 2.1 Various Principles of Preform Fabric Manufacture Techniques

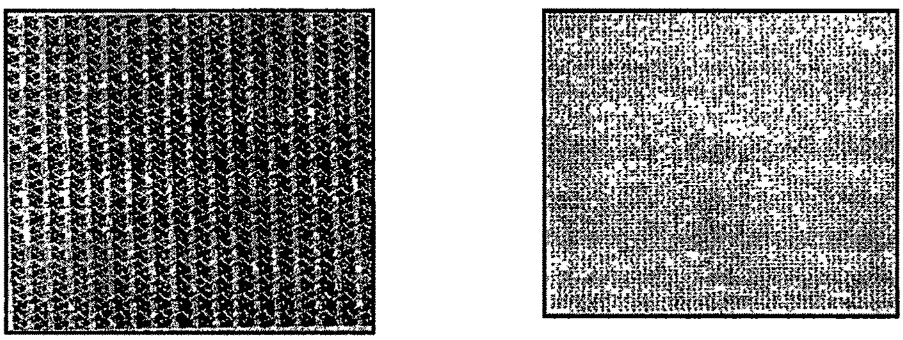
| Sr. No. | Method of fabric manufacture | Direction of fibre/yarn laid | Fabric formation principle |
|---|---|---|---|
| 1 | Weaving | 2D | Interlacing |
| 2 | Knitting | 1D | Interlooping |
| 3 | Braiding | 1D | Intertwining |
| 4 | Nonwoven | 3D or multi directional | Bonding of Oriented fibre |

***a) Woven Preforms***

Woven textiles, both narrow and broadcloth, are the most commonly used preform materials in manufacturing of composites. The weaving process mainly comprising of weft insertion technologies viz. shuttle, rapier, projectile and air-jet. Rapier looms are the most popular type as they can handle a variety of yarns where as the shuttle looms equipped with electronic jacquard are popular for weaving 3D shell structures. Most commonly used weaves are plain, twill, matt and satin. The plain weaves have lowest tensile stiffness and highest in-plane shear stiffness. On the other hand, satin weaves have relatively straight yarns resulting in highest tensile stiffness and lowest in-plane shear stiffness. Matt weave exhibits properties in between plain and satin weaves. Satin weaves are easy to drape on complex mould surfaces and the resulting composites exhibit highest stiffness, closer to unidirectional laminates. Plain-woven composites, on the other hand, exhibit highest toughness.




(a) Preform structures



(b) Preforms

Fig. 2.10 Various types of perform structures and preforms



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***b) Knitted and Braided Preforms***

Knitted fabrics can be formed into complex shapes and are generally used in secondary structures where component stiffness is a secondary factor. These preforms used as composites have applications in impact energy absorption. Multi-axial stitch bonded fabrics have relatively straight yarn held together by a monofilament polyester yarn. These fabrics are highly comfortable and have in-plane properties comparable to those of unidirectional laminates. Braided structures are promising for relatively narrow complex shapes such as propeller shafts, coil springs, rotor blades, rocket exit cones etc. On going research at UMIST includes the development of a computerized controlled 3D braiding machine for producing complex shaped parts[6].

***c) Nonwoven Preforms***

Nonwoven structures are fibre-to-fibre assemblies produced using bonding technique, by chemical, thermal or mechanical means or a combination of them. Nonwoven based composites are used wildly in automotive, marine and other applications. The method to develop composite material by coating nonwoven fabric made of carbon fibre or a blend of carbon fibre and other organic fibre with a filler containing liquid has been described in patent[9].

***d) Three-dimensional Preforms***

Three-dimensional woven fabrics have been developed to further improve the performance of textile composites. Through-the-thickness reinforcements in the form of orthogonal and angle interlock weaves provide superior inter-laminar strength and damage tolerance to composites. These 3D fabrics can be woven on conventional weaving machines or purpose built 3D weaving machine. Shell structures have been produced at UMIST on a conventional shuttle loom equipped with an electronic jacquard. These 3D shell structures avoid the need for joining.

***e) Preforms from Commingled yarn***

Commingled roving in yarn form has now become quite popular for making many kinds of textiles, such as woven, knitted and braided preforms. In most applications, they replace pure reinforcement roving for improvement of the final product. Due to their inherently even mixture of reinforcement fibres and matrix material, they usually yield a homogeneous distribution of fibres in the composite[1].

### 2.4.2 Characteristics of Textile Preforms

The essential properties of textile preform for composites include, high tensile strength, high flexibility, formability, stability and high axial rigidity. Table 2.2[9] shows some of the important properties of various type of structured textile performs. Consideration of geometrical properties in designing textile preforms will help to predict the resistance of preforms to mechanical deformations such as initial extension, bending and shear in terms of resistance to deformation of individual fibres. In high-tech applications of composite, the preform should posses better impact resistance, fire resistance and stability at high temperatures.

Chen and Chou[10] studied the mechanical properties of multilayer and angle interlock woven structures. They observed that 3D woven structures heavily depend on the fabric structure. Many researchers used kinematics approach to study the deformation behaviour of textile fabrics. 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, fibre volume fraction etc. Although the various technologies available for manufacturing composites, only liquid composite molding has the capability of manufacturing polymer composites with large size and complex shape at low cost.

With improved textile preforming techniques in combination with developments in characterization of fibre structure, the production and processing of fibre and textile materials now help to achieve outstanding composite properties. Better understanding of the functional performance of reinforcing fibres in composite materials enables design and production of new textile based composites for wide range of application. Thus optimization of traditional textile technologies will help to reduce manufacturing cost of advance composites.

Table 2.2 Characteristics of Various Types of Textile Preforms

| Textile preform | Advantages | Limitations |
|---|---|---|
| Low crimp Unidirectional | 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 |
| 2D Woven | Good in-plane properties; good friability, highly automated preform 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 |
| 3D 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 |
| 2D 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 |
| 3D 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 Wrap knit | Good taliorability for balanced in-plane properties; highly automated preform fabrication process; multilayer 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 |

## 2.5 DIFFERENT HYBRID YARN STRUCTURES

The hybrid yarns consist of reinforcing and matrix filaments combined together to give proper architecture to the preforms structures. The use of different polymer type of matrix and reinforcing fibre and filaments in core-sheath combinations provides particular characteristics of hybrid yarn. The properties of composites are greatly affected by the arrangement of reinforcing fibres and homogeneity of the fibre distribution in the composite. The hybrid yarn structures developed basically depend on the yarn manufacturing technology. The Fig 2.11 shows schematic representation of various types of hybrid yarn structures obtained using different technique of hybrid yarn manufacture viz[11].

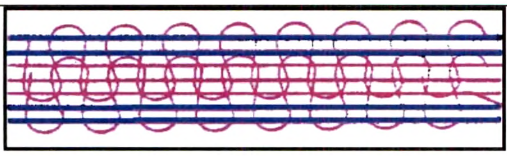
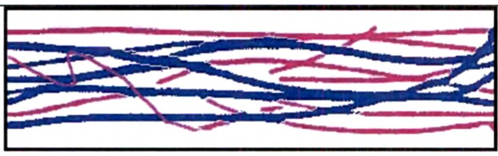
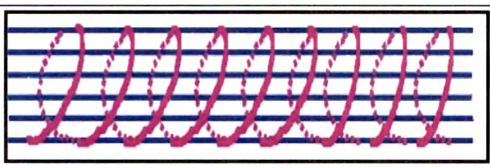
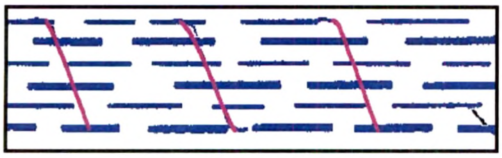
| Hybrid yarn structures | Orientation of component fibre |
|---|---|
|  | Straight and parallel arrangement of reinforcing and matrix filaments without mixing |
| Side By Side(SBS) | |
|  | Parallel arrangement of matrix filaments surrounded by parallel reinforcing fibres in the core, sheath by matrix fibres in |
| Kemafil technology(KEM) | |
|  | Reinforcing and matrix filaments are commingled; the arrangement of reinforcing fiber is out of yarn axis |
| Commingling technique(COM) | |
|  | Parallel arrangement of reinforcing filament in core and staple fibres wound spirally in the skin |
| Friction spinning technique(FS) | |
|  | Mixture of discontinuous reinforcing and matrix fibers surrounded by continous matrix filament |
| Schappe technology(SCH) (Cover spinning technique) | |
| ■ Reinforced filaments ■ Matrix filament | |

Fig 2.11 Different structures of hybrid yarns showing fibre orientation

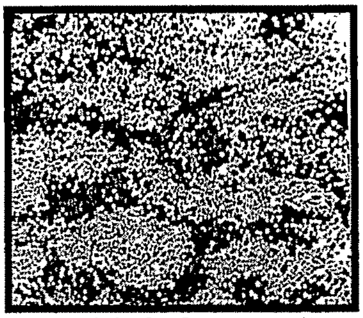
- Parallel arrangement of matrix fibre and reinforced fibres side by side (SBS)
- Parallel arrangement of matrix fibres surrounded by parallel reinforcing filaments in the core, sheathed by matrix fibres in the skin resulting from 'kemafil' technology (KEM)

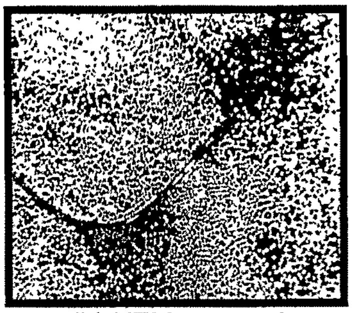
- Parallel arrangement of reinforcing fibre in the core and spun fibre in the skin using friction-spinning technique (FS)
- Mixture of discontinuous reinforcing and matrix surrounded by continuous matrix filaments using Schappe Technology(SCH)
- Commingled matrix and reinforced filament by air texturing or interlacing commingled yarn(COM).

B. Lauke et.al[11] have given comparative analysis of composites of glass/ polyamide-6 hybrid yarn made using different yarn manufacturing methods. The Scanning Electron Micrograph(SEM) of these yarns in composite shows that homogeneity of fibre distribution within the matrix is different in each case depending on yarn manufacturing technique(Fig. 2.12). The SCH and COM composites show fairly homogenous mixture of reinforce and matrix fibres. The proper impregnation of reinforcing fiber with matrix material mainly depends on the degree of mixing. Even If all the parameters are compared, then too the SCH and COM hybrid yarns are the best but the only problem with COM yarn is that the polymer fibre and reinforcing fibre unmingled on application of tension, due to the difference of stiffness value which gives uneven fibre distribution in the final composite. Otherwise in commingling process the reinforcing and matrix filaments are intimately mixed in a nozzle by means of compressed air. Among these hybrid yarns commingled yarns provide high potential for thorough blending of matrix forming filaments and high-performance fibers. This process is versatile and gives soft, flexible and drapable yarn. This has made commingling technology suitable for textile preforming process to produce high-performance composites[14]. Combination of commingling and co-wrapping may give a yarn with very good matrix/ reinforcement distribution and good protection of the reinforcing fibers.

### 2.5.1 New Hybrid Yarns for Continuous Fibre Thermoplastic Composite

New hybrid yarns for continuous fibre reinforced thermoplastic composites are under investigation for last 15 years. The first work reported by Klein using carbon reinforcing material coated with thermoplastic powder to improve the mechanical properties of composites. During the research they observed that thermoplastic composites having higher impact resistance and better resistance to atmosphere. Also the flexibility improves due to higher elongation of thermoplastic polymers.


(a) SBS composite


(b) KEM composite


(c) COM composite


(d) FS composite

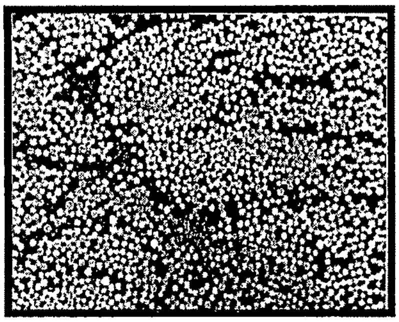

(e) SCH composite

Fig 2.12 SEM of distribution of reinforce and matrix material in final composite in different type of hybrid yarn structure

Denkendrof et al. started their work on developing hybrid structures using multifilament composed of reinforcing filament and thermoplastic filaments for preforms structure, which is finally converted into thermoplastic lamination. Saint-Gobain Vetrotex has developed a patented commingling process for glass and polypropylene yarn (Twintex). The manufacturing route consists of drawing and sizing glass fibres, which are then passed to an annular drawing head that is supplied with molten polypropylene from an extruder.

An alternative approach by Schappe blends stretch-broken carbon fibre with polyamide and staple fibres with addition of a wrapping filament, which is available commercially. A final approach to commingling is developed for carbon and polyetheretherketone(PEEK) system. This system gives homogenous distribution. Same method is tried with different combinations of material viz. glass/polypropylene, glass/polyester, glass/nylon, carbon/ polypropylene, carbon/polyester, etc. using different method of yarn manufacturing. Recently some of the works reported on commingling process for hybrid yarn from Dresden University, Germany and IIT, New Dellhi, under which studies on hybrid yarn structure process behaviour and air flow analysis are respectively under investigation.

## 2.6 COMMINGLING PROCESS

### 2.6.1 Basic Principle of Commingling Process

Mingling process of two or more yarns to form a single strand of yarn can be defined as commingling[12]. Synonyms terms to 'mingling' are interlacing, tangling, entangling, intermingling, and commingling. In the commingling process, rapidly moving air in a nozzle generates entanglements among the filaments forming the bulky thread. Fig. 2.13 shows the schematic diagram of the commingling process.

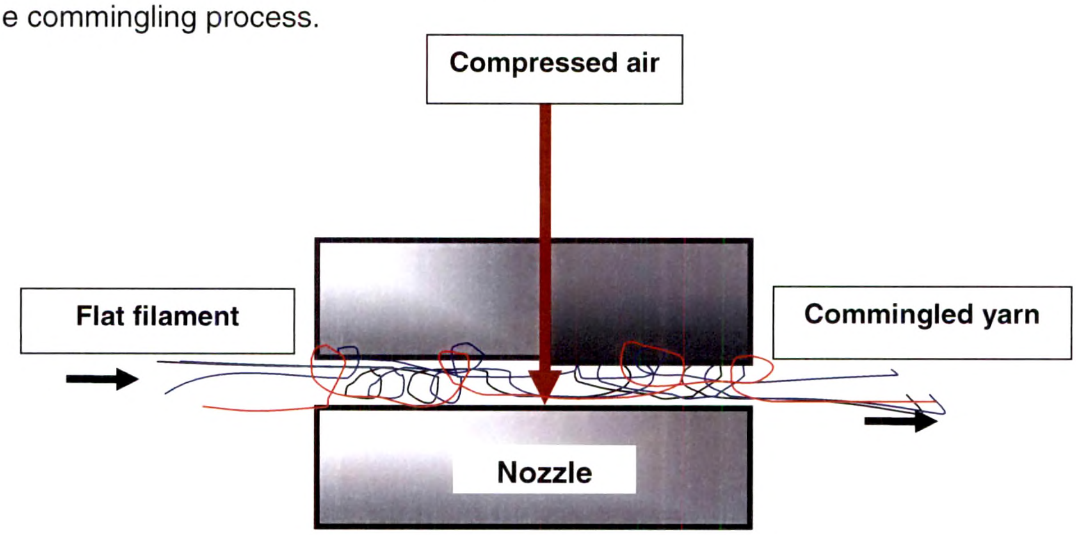



Fig: 2.13 Schematic diagram showing commingling principle

Cohesive forces between the fibres and filaments are essential to hold the fiber and filaments bundled together to form a flexible structure such as textile yarn. When a loose bundle of filaments are instantaneously subjected to the effect of a turbulent cold air-jet impinging on them at right angle, the air flow opens up the filaments, while in the immediate vicinity of the opened up section of the filaments are intertwined and mingled with each other to form a compact section. Thus, cohesion is imparted to an originally loose bundle of filament. The basic filament structure, either physically or chemically, does not change but the position of filaments is altered.

Commingled yarn consists of blended combinations of reinforcing filament yarn and filament yarn spun from thermoplastic polymers. The multifilament yarns are scattered among one another at the filament level. By using the commingling process; any weaveable reinforcing fiber and most spinnable polymer fibers can be combined[14] When heat is applied, the thermoplastic component melts and wets the reinforcing component and forms amorphous reinforcing binder. After subsequent cooling, the system is transferred into composite material. A homogeneous distribution of the reinforcement and matrix would reduce the mass transfer distance of the matrix during processing, which will lead to a fast and complete impregnation of the reinforcement filaments. In combination with the developments in textile structures, use of commingled yarns significantly improves the mechanical properties of the resultant composite parts. Several patents are claimed on the commingling of high-performance and matrix-forming filaments for composites and other applications.

### 2.6.2 Basic Airflow Analysis

Basic airflow analysis of mingling nozzle is done by many of the scientists. The main behaviour of air-jet inside depends upon the nozzle geometrical configuration of the nozzle. An analysis of commingling process is based on the general theory of hydraulics and pneumatics. The fluid flows are categorized in two types.

*(1) Laminar*

*(2)Turbulent*

The airflow in texturing or mingling process in a cylindrical cavity is turbulent flow which can be expressed by Reynold's numbers

$$\mathbf{Re = vd/\lambda}$$

Where v = speed of the air stream

d = pipe diameter

$\lambda$ = kinetic viscosity factor

The Reynold's number at which the transition from laminar to turbulent flow occur is called the critical Reynold's number ($R_{cr} = 2200$)

If **$R_e > R_{cr} \rightarrow$ Turbulent ($R_{cr} > 4000$)**

**$R_e < R_{cr} \rightarrow$ Laminar ($R_{cr} < 2000$)**

The critical Reynold's number changes with cross section of the pipe and affects the magnitude of flow.

The basic equation for compressible fluids,

$$\frac{dA}{A} = \frac{dV}{V}\left[\left(\frac{v}{c}\right)^2 - 1\right]$$

$$= \frac{-dV}{V}\left(1 - M^2\right) \qquad \text{-------- } (1)$$

The speed at which an infinite disturbance would propagate through a fluid medium has a fundamental importance in the study of compressible flow. The ratio of actual velocity 'V' and Speed of sound 'C' is known as Mach number 'M'. In compressed air two phenomena occur as the fluid Velocity V approaches C.

- The pressure drop in internal flows is significantly large.
- Disturbances due to body placed in flow would not propagate in the up stream direction.

By using of equation (1)

**Case I V < C, M < 1 Subsonic flow**

$$\frac{dA}{A} \propto -\frac{dV}{V}$$

If area increases, velocity decreases for incompressible flow.

**Case II V = C, M = 1 Sonic**

$$\frac{dA}{A} = 0$$

Where the change in area is zero at the end of a convergent passage.

**Case III V > C, M > 1 Super sonic**

$$\frac{dA}{A} \propto \frac{dV}{V}$$

If area increases velocity increases.

In the case of intermingling nozzle, the incoming airflow having divided into two branches, creates the free jets at both ends of the yarn channel. Due to sudden opening of inlet hole into the main duct, abrupt energy loss is inevitable. The oblique opening of inlet hole deflects the coming jet backward and consequently increases the cohesion to the opposite wall, causing permanent energy loss.

### 2.6.3 Commingled Yarn Structures

The commingling yarn structure basically consisting of open and nip structures are categorized in to four classes[17] (Fig. 2.14).

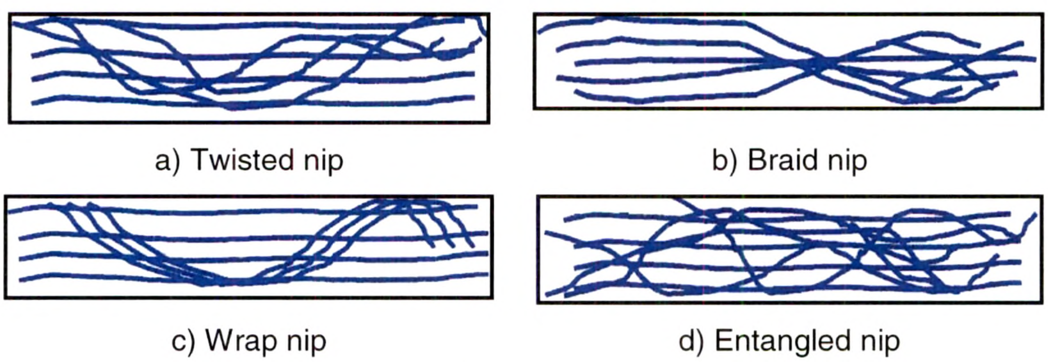



Fig. 2.14 Various nip structures



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***a) Twisted nip***

Filament in this nip structure class show dominant twisted yarn characteristic, because the twist is inserted while the yarn is held at both sides, the structure is false twist in nature. Twist nips are formed mainly because yarn has not been sufficiently opened during the first phase of the interlacing process.

***b) Braid nip***

The braids are typically composed of three intertwined filament bundless though more than three bundles can also form braids. The yarn opens into two bundles at the initial interlacing phase. In this case process is similar to ply yarn.

***c) Wrap nip***

If the yarn divided in to two or more filament of different size, one of the bundles consists of only one or very few filaments. This minor bundle may be pulled out by the strong air jet and become wrapped on the main bundle. The presence of wrap nips help to improve nip structure stability.

***d) Entangled nips***

Entangled nips are featured by filament disorganization and therefore do not show unique structural pattern. When the filaments are divided into many small branches during the initial opening phase, the small bundles mingled together and run closely forming a messy entangled nip structure.

## 2.7 FACTORS AFFECTING COMMINGLING PROCESS

A characteristic of mingled yarn depends upon raw material characteristics and commingling process parameters. The parameters that influence the structure and properties of commingled yarns can be divided into following three groups:

- *Raw material parameters*: filament denier, number of filament, cross sectional shape of fibres, filament rigidity and frictional characteristics of filaments



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- *Process parameters:* air-pressure, overfeed ratio, take-up speed and winding tension
- *Nozzle design and settings*: nozzle type and nozzle design

### 2.7.1 Effect of Raw Material Parameters

Some basic studies, which are carried out aiming to understand fibre-air interactions during texturing or mingling, are reported in literature[21]. During texturing, filaments are subjected to bending and torsional deflections under fluid forces. Filaments with a lower bending and torsional stiffness will facilitate the loop formation process. For finer filament yarns smaller drag force is necessary because they offer smaller bending and torsional stiffness. Whereas in case of coarser filament yarn greater force will be required to overcome their inertial resistance[23].

With an increase in the number of filaments, the potential for mutual filament entanglements also increases, causing yarns with a higher number of filaments to texture better than those with fewer filaments. Demir et al.[24] observed that with an increase in filament linear density, instability in yarns first increases and then decreases with further increase in the filament yarn linear density. The authors also commented that the finer filament yarns had better mass uniformity than coarser filament yarns. However, finer filaments below certain denier may not be suitable for certain nozzle parameters and process parameters. The cross section of filaments will determine the area-dependent mechanical properties of filaments. Different cross sections therefore need varying forces to deflect the filaments. Acar[23] analyzed the effect of cross-sectional shape of filaments on loop formation. The author observed that elliptical and hollow circular cross-sectional filaments texturize better than those with solid circular cross section. Further he explained that noncircular and hollow filaments having larger surface area than circular filaments of equal linear density are subjected to greater frictional drag forces relative to their inertias. Therefore, certain filament yarns with noncircular cross sections are more suitable for improved air jet texturing than yarns with circular cross sections.

Extensive research in the area of filament behaviour in air jet shows that the most important factor in processing of continuous filament yarns in air jet is the fluid forces acting on filaments. These studies also presented experimental support on air-filament interactions in the air jet. From these results it can be observed that the action of the jet on filaments is a function of the difference between the force generated by primary and secondary flows and the friction drag. The forwarding force acting on the filaments depends on different specifications such as, total surface area, fineness, number, cross section, and frictional characteristics and rigidity of filaments. Above studies on air-filament interactions primarily involved various matrix-forming filaments such as nylon, polyester, and polypropylene. However, detailed studies are needed to understand interaction of air with high-performance yarns/matrix-forming yarns.

### 2.7.2 Process Variables

#### *a) Air pressure*

Airflow velocity is the main driving force, which is responsible for opening up the filaments and enabling them to entangle with each other. With the increase in air pressure, flow velocity also increases. The effect of airflow rate is also the same as that of air pressure[25]. The air pressure required for mingling is usually up to 3 kg/cm$^2$, whereas for air jet texturing it is between 8 and 10 kg/cm$^2$. With increase in air pressure, nip frequency increases, however after a certain limit, frequency decreases rapidly. Increasing the air pressure increases the number of mingling points inserted into the yarn[26]. However it depends on the type of jets used. Chono et al.[27] carried out their experiments with intermittent air jets in air jet interlacing equipment and observed that with increase in blowing frequency, the probability of entangling parts decreases rapidly because of the effects of mutual interference and period of air blowing. The authors also found that, with increase in air pressure the number of nips per unit length also increases slowly. For higher air pressure the rate of increase in nip frequency is found to be small. Lemoto and Chono[28] studied the airflow field in a yarn path by measuring the pressure distributions at the surface of a yarn duct and the flow velocity distributions near the surface of a yarn duct of intermingling nozzle. Their experiments show that flow pattern in the yarn duct does not depend on pressure.

***b) Overfeed***

Overfeed of the multifilament yarns during texturing can be done to move some filaments faster than others. With an increase in overfeed the availability of free length of filaments for forming loops increases. With an increase in overfeed texturing efficiency and yarn linear density also increases, but loop stability reduces. Decrease in yarn tenacity has been observed with an increase in overfeed.

In mingling of the yarn, the over feed is either zero or very low. An experiment carried out by Imeoto et.al.[28] found that the maximum nip frequency is obtained at about 1% overfeed. Another study shows that the number of tangles increases with the increasing feed ratio up to some extent, there after it decreases with increase in feed ratio. This is because at lower feed ratio the tension exerted on yarn is higher, resulting into lower number of tangles, but as feed ratio increase, the nip frequency increases as tangling of yarn becomes easy, but as the feed ratio increases further, yarn tension reduces and yarn may move out of the potential action of air and therefore the nip frequency decreases.

***c) Take-up Speed***

In mingled yarns, the effect of take-up speed is not very much clear as research reports illustrate some degree of contradiction between each other. Whilst the results of Sparke, Lunenschloss and Zilg, working in similar speed range, i.e., upto 800 m/min show deterioration in nip frequency or difficulty in mingling, Weinsdorfer, working at somewhat higher speeds, i.e., upto 1500 m/min., indicates an increase in nip frequency with increasing yarn speed. Weinsdorfer obtained these results from a circular channeled nozzle; further results using second nozzle with semi-circular cross-section, however, indicates a decrease in nip frequency at speeds exceeding 1000 m/min. It is likely that different nozzle configurations and yarn properties result in different mingling conditions that result in variation in nip frequency.

*d) Yarn tension*

There is an optimum tension value at which the maximum nip density is obtained. A higher yarn tension than this, obstructs the free vibration of the filaments resulting in poor mingling. On the other hand, if the tension is too low, then the whole bundle of filaments could easily slip out of the jet's potential area causing a failure of mingling. It has been deduced that the necessary optimum tension would be a function of the nozzle, yarn and process conditions, as no such unique value is provided by any researcher. Over and above the effects of process parameters, it is also experienced that entangling process becomes easier at lower temperature conditions.

### 2.7.3 Design of Nozzle

*a) Effect of Nozzle Design*

Design of air jet nozzle largely depends upon the type of supply yarn and its end use applications; therefore it is very difficult to develop jet designs for wide application range. Being at the heart of entire air texturing or commingling processes, many specific purpose jet configurations have been developed predominantly through practical experiences rather than by informed theoretical considerations. Demir et. al[24] reported the findings regarding the influence of parameters on air flow and noise level. Fig. 2.15 shows classification of intermingling nozzles based on various design aspects. Various type of the mingling nozzles are designed using different parameters such as type of yarn threading facility, pattern of air supply, cross sectional shape of yarn channel, longitudinal shape of yarn channel, type of air entry, angle of air entry channel and positioning of air nozzle etc. The velocity profile of the jet is governed by a combined effect of the following nozzle parameters.

- Cross sectional area of the air inlet hole.
- Cross sectional area of the yarn channel
- Cross sectional shape of the channel.

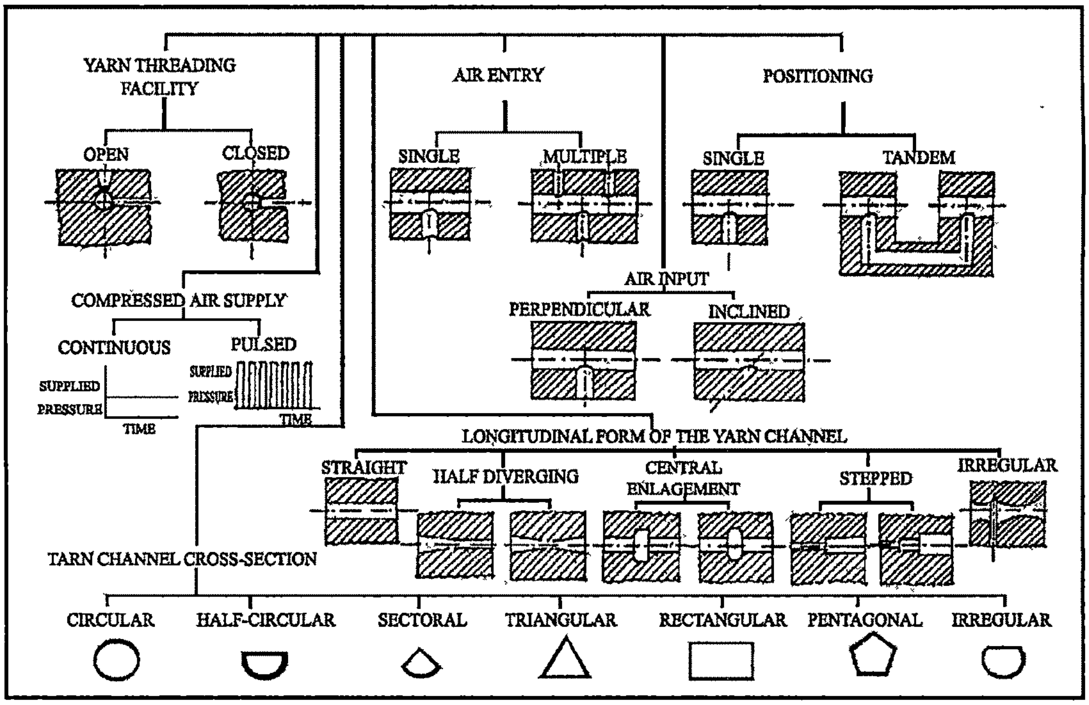



Fig. 2.15 various design of mingling nozzle

- Angle between air inlet hole and yarn channel.
- Length of yarn channel.
- Surface finish of yarn channel

1) Cross-sectional area and Inclination of air inlet hole

As reported by Chono et.al.[29], with the use of smaller cross-section of the air blowing orifice, the interlocking effect is improved as a result of increase of air velocity. Lunenschlos and Zilg[30] investigated that the larger diameter of inlet hole permits higher mingling densities due to the higher kinetic energy of the incoming jet.

As suggested by Schubert[19], an oblique air inlet will increase the mingling density but could disturb the line tension. But, it would be worthwhile to note that almost all the manufacturers of jets today rely only on the right-angled air entry. In mingling nozzles, the incoming airflow, having divided into two branches, creates free jets at both ends of the yarn channel. This division of the flow into two branches in the channel is mainly governed by the angle of inlet hole with respect to the main channel. A perpendicular inlet hole causes an equal division of the flow, while any slight variation from the right angle results in an unequal division.

2) Length of yarn channel

As per the opinion of Lunenschlos and zilg[30] the shorter yarn duct always exhibits lower mingling density. They explained this by the change in the flow conditions, which is not elaborated further. Lazauskas et.al[35] on the other hand, has found that with an increase in the yarn channel length, the nip frequency decreases. Lazauskas et.al.[35] explained this by the build-up of a static pressure within the channel. Thus Long yarn channel allow the outgoing flows to expand and develop within the channel and create a uniform air velocity profile whereas the non-uniformity in the velocity profile increases with shorter yarn channel length.

3) Cross-sectional shape of yarn channel

Referring to the results of Kaczynski, Schubert claims that a yarn channel with a rectangular cross section will lead to greater mingling density than the round yarn channel. It is claimed that this is due to the outward reflection of the incoming jet at the opposing flat surface of the rectangular yarn duct, while this reflection is inward and uncontrolled in the case of a round yarn channel, Weindorfer[32] showed that the shape of the yarn channel cross-section is of great importance for the effectiveness of nozzle. He also agrees with the conclusion of Schubert that a rectangular cross-section is superior to semi-circle, which is better than that of a round channel.

Lazauskas et. al.[35] studied the effect of yarn channel using various cross-sectional shape viz. circular, semi-circular and a sectoral and stated that where the yarn channel cross-section was not circular, the mingling tended to become less intense. This conclusion is explained by the observations that the filament tends to move out of the most turbulent zone formed by the incoming jets.

4) Cross-sectional area

Hintsch and Michel[19] have observed that the yarn channel having lesser diameter produces intense interlacing. It is however emphasized that the yarn channel diameter should be determined according to linear density of the yarn to be mingled.

5) Longitudinal form

Schubert has reported that reductions in the channel cross-sectional area at both ends could deteriorate the nozzle effectiveness. An extensive research is still awaited to study the influence of this variable on the efficiency of interlacing.

6) Surface finish

Sparkes in his investigation concluded that a nozzle could only perform effectively if the surface roughness of the channel is less than 0.4 mRa. However, there is no other report in the literature that gives such a great importance to the surface finish of the channel.

The prime objective of the commingling process is thorough blending of matrix-forming and high-performance filaments by means of compressed air. When two or more yarns are directed through the yarn chamber of a jet, they vibrate rapidly between the upper and lower air vortices. The frequency of yarn rotations inside the jet mainly depends on which vortex the yarn is strained. The nip frequency of commingled yarns is the function of the speed of rotation of the vortex. The frequency of air vortex generated mainly depends on the air pressure and the jet design. If the air entry orifice does not intersect the centerline of the jet, one of the vortices may be predominant and the yarn will be retained in that predominant vortex, and may be twisted in one direction without any commingling effect.

With greater forwarding capacity, the texturing jet provides less commingling action. It is generally very difficult to develop compact commingled yarn with homogeneous distribution of matrix and reinforcing fibers with forwarding jets.

Therefore, it is very important to develop suitable jet design, which will provide compact and stable commingled yarns with uniform dispersion of reinforcement fibers and matrix-forming fibers. Detailed analysis of airflow profile in commingling jets with respect to high-performance fibers like glass and carbon may help to design and develop the required commingling jet. Recently some researchers reported computarized fluid simulation methods aiming to understand the flow profile inside air jets.

***b) Influence of jet design on blend homogeneity***

Many researchers have described the techniques to determine blend uniformity in staple fibre yarns[36]. The methods to analyze blend irregularity can be classified into categories such as longitudinal blend irregularity, radial blend irregularity, and rotational blend irregularity. Renagasamy et.al.[21] has studied rotational blend irregularity of nylon-nylon; nylon-PET, and PET-PET parallel fed multifilament air jet-textured yarns. They observed that a close association exists between Index of Blend Irregularity [I.B.I] values and delivery zone tensions, indicating an improvement in the blend homogeneity with the increase in delivery zone tension. The authors also observed that a sufficient number of filaments in the yarn cross section are essential for better structural integrity[37]. According to them, the potential for blend uniformity will improve with the use of finer denier per filament and higher number of filaments. Cylindrical nozzles with higher filament yarn velocity and relatively lower air consumption rate give better results for blending of finer filaments.

Gupte et. al.[38] extensively studied the influence of process variables on the blend homogeneity. The author used packing density, normalized radial and lateral distribution, and clumpiness parameters to determine the blend uniformity. With the increase in jet diameter, packaging densities decreased nonlinearly for both the components. The jets with three air inlet holes produced the least blending over a cross section together with a greater variation along the length of the yarn. He also observed that the packing density was reduced for a take up speed in the range of 320-430 m/min, but with a further increase in speed, packing density increased.

Thus, the author concluded that the highest overall levels of packing density were generated with air pressure of 8kg/cm$^2$. The normalized radial distribution parameters showed their maximum values of pressure at 8.5 kg/cm$^2$ beyond which a reverse effect was observed. Aggregation Index (A.I) was found to be lower at higher air pressure and the lowest A.I. was observed around a pressure of 8kg/cm$^2$, which according to the author was due to inadequate air turbulence giving ineffective texturing and blending. As the core yarn overfeed was increased, packing densities of both types of filaments increased in the core region and the overall packing density was also found to increase significantly. However, radial distribution of different filaments over the cross section did not vary significantly. Clumpiness of the yarn was found to be reduced with increase in core yarn overfeed.

## 2.8 DEVELOPMENT IN AIR TEXTURING/COMMINGLING MACHINES

The development of machines for new processes with advance technology in air texturing/commingling process are capturing the market due to its wide range of applications viz. sewing thread applications, apparel fabrics, fancy yarn articles, automotive interior fittings, and home furnishing fabrics, carpets, fire blankets and a wide range of other industrial applications. The air texturing/commingled yarns are produced from thermoplastic, cellulosic or non-organic filament yarns using compressed air. Loops or nip structures are formed on the surface of the filament yarn, which binds the filaments of same characteristics or two different characteristics together.

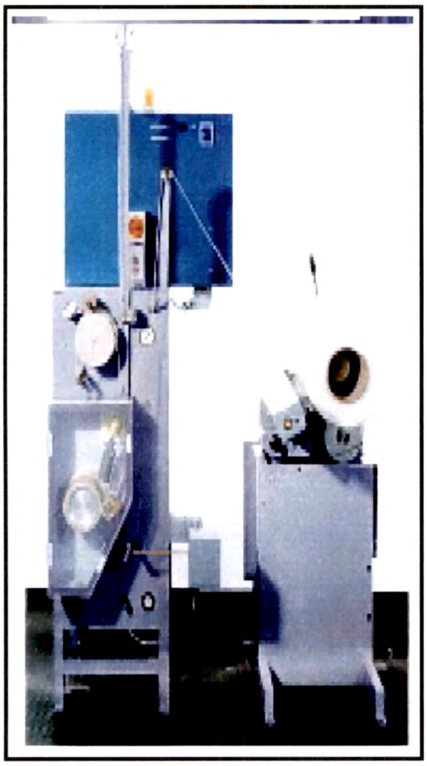
In air texturing process depending on the material used, optimum processing parameters setting and proper selection of nozzle gives the loop structure, resulting in a yarn with characteristics resembling those of conventional staple-fibre yarn. In recent days the commingling process of hybrid yarn with nip characteristics is capturing the market due to its homogenous mix for different thermoplastic composite application. The trend of modifying existing machines to produce technical yarn for different technical application has been seen in ITMA 03[42].

### 2.8.1 Air Texturing Machine

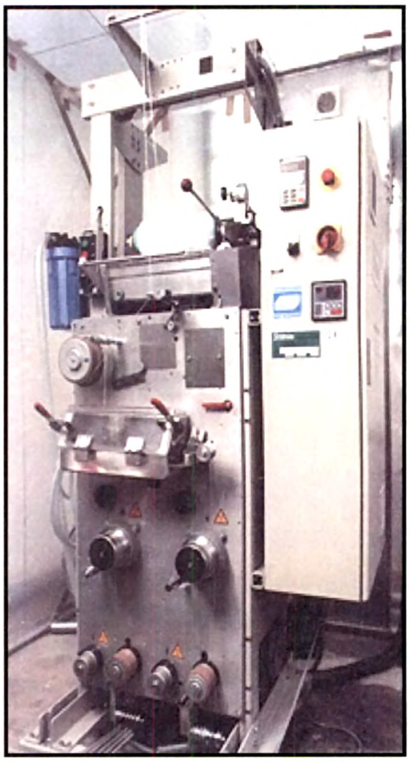
The air texturing machine consists of a supply yarn creel, a suitable winding head fitted with yarn transport including extra pair of feed rollers and air jet. Traditionally, air texturing machines had individual drive(SSM Staehle) and line shaft machine with headstock (Guidici, ICBT and RPR).Due to their ability to process a very wide range of yarns and the fact that each machine position could be set up to produce a different yarn, machines with individual drives have become the norm in present day technology. Apart from few developments in winding technology applied to air-texturing machinery and the method of water application, the development of air texturing over the yarns has been dependent on the development of air-jet nozzle technology, which gives the possibility of processing of a wider range of yarns at greater processing speeds, lower energy consumptions and lower noise levels.

The major exhibitors of Textile machinery at ITMA 2003 in Birmingham U.K. were Dietze & Schell Maschinenfabrik GmBH, Germany and SSM Staehle Eltex GmBH, Germany. Dietze & Schell[41] presented their DS 60, DS 90E, DS 60D and DS 90MFB air texturing units as shown in Fig.2.16. All of them are primarily designed to texture glass fibres using Heberlein and custom in-house jets. This system prevents the filament breakages. The ranges of glass yarn or roving can be used from 68tex to 5000 tex. Except for DS 90MFB, which has a maximum production speed of 300 m/min, the other models have production speeds in range of 100–600 m/min.

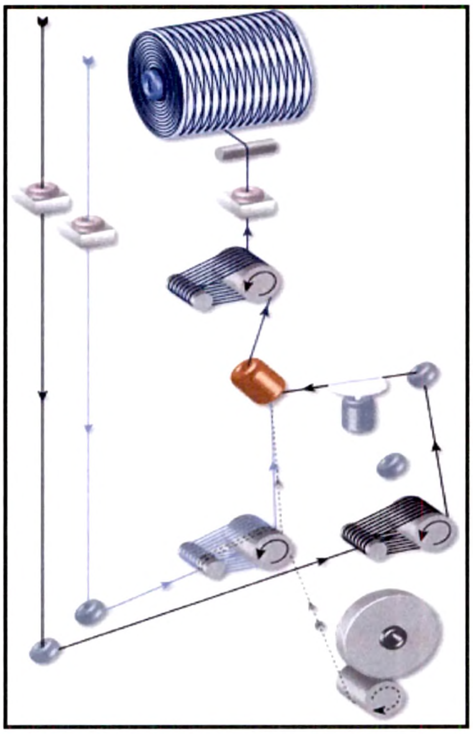
The new model of SSM Stahle RM3-T and DP2-T air-texturing units are shown in Fig. 2.16 (c) and (d). The DP2-T textures yarns from fine to medium filament yarns up to 900 dtex, while RM3-T is designed to texture high linear density yarns up to 3200 dtex. Both these machines are designed to run at production speeds as high as 100 m/min. They are also equipped with a sound box that includes a yarn wetting device, rubber coated cold feeding elements for slip-free feeding and chromium plated half polished heated feeding elements.



a) DS 90 MFB



b) DS 90 E



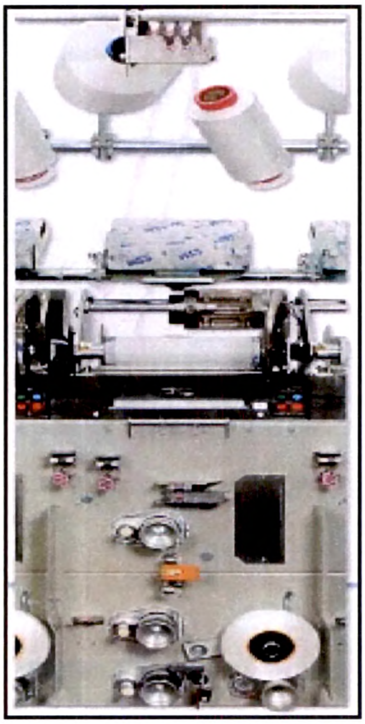
c) DT2-T SSM Staehle


d) RM3-T Digicon SSM Staehle

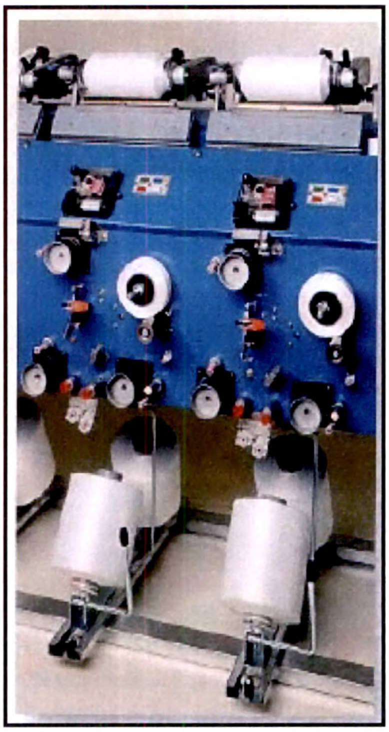
Fig. 2.16 Air texturing units

### 2.8.2 Commingling Machine

The intermingling/commingling machinery displayed at ITMA 2003 was primarily concerned with producing air-covered yarns with elastane component covered by a continous filament yarn or staple fibre yarn. Stahle DP3 C model, from SSM Stahle (Fig. 2.17(a)) and air covering unit displayed by FADIS (Fig. 2.17(a)) both these machines employed the Heberlein Slidejet and the Heberlein Spunjet nozzles for their processes[44].



a) Stahle DP3 C



b) Fadis Air Covering Unit

Fig. 2.17 Commingling machines

### 2.8.3 Development in Nozzle Technology

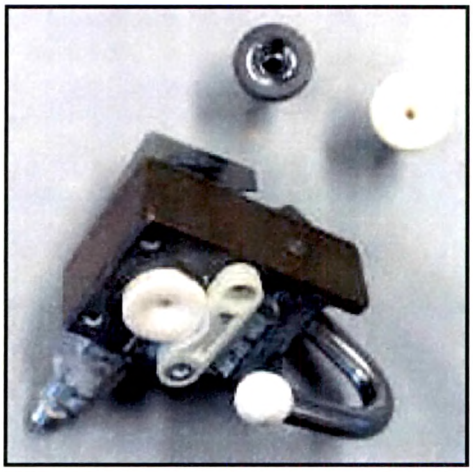
Heberlein Fibre Technology Inc., Switzerland, TEMCO GmBH, Germany and Fibreguide Ltd, U.K. were the major air-texturing/commingling nozzle manufacturers.

#### *a) Air-texturing nozzles*

Heberlein Fibre Technology Inc. introduced its new line of ceramic nozzles under the A-series trademark as shown in Fig. 2.18. These included the A317, A327, A347 and A357, with each subsequent nozzle being able to texture higher linear density yarns. This A-series nozzle claim to reduce the noise as well as minimize compressed air consumption compared to the other commercially available air nozzle and also give compact yarns, afford higher process stability compared to the T-Series and provide better blending[40].

#### *b) Commingling /interlacing nozzles*

Heberlein, displayed their popular Slidejet and Spunjet series shown in Fig. 2.19(a). Fibreguide presented their FG5 all purpose interlaces, FG 8 continuous interlace of micro denier yarn and FG10M for interlacing between godets and uniform oil distribution series of interlacing jets as shown in Fig.2.19(b) .



LB 341


EO52

Fig. 2.18 Heberlein: Air texturing jet



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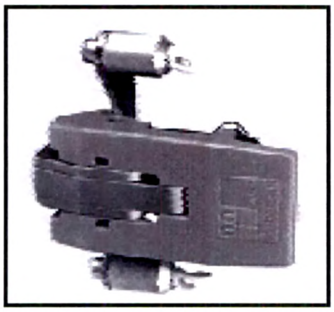
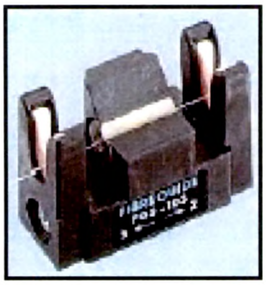


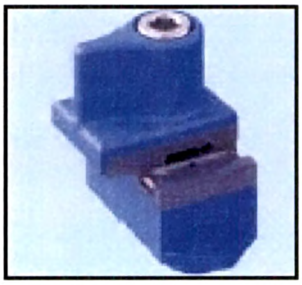
DT

FT

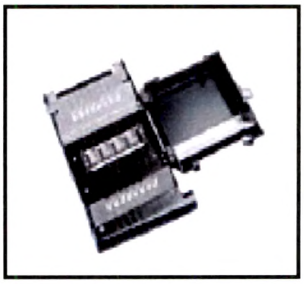
a) Heberlein :slidjet



FG 8



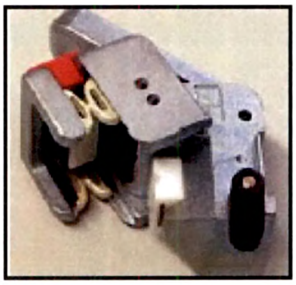
FG5



FG 10M

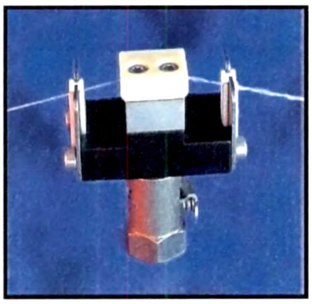
b) Fibreguide

Y-Profile



LD 22

c) TEMCO jet



Interlace jet for Technical yarn

Fig. 2.19 interlacing jets

TEMCO[43], Germany featured their Y-Profile jet LD22 shown in Fig.2. 19(c) that may be used to intermingle flat or textured yarns. The Y-technology is based on special flow office geometry and its location in the jet yarn path. TEMCO claim that this y-profile gives the interlacing nips, a very high stability as well as uniformity over the length of the yarns.

### 2.8.4 Covering Machine

TEMCO have developed a machine comprising of belt driven spindles for the cover spinning of elastomer with synthetic yarns or with natural yarns. Based on the experience of the belt driven spindles, and on many years of know-how in the field of individual motor driven spindles, TEMCO have launched the MSE150, which has been designed in accordance with its corresponding bobbin weight and bobbin geometry (up to 6.5" traverse) for high rotational speed (Fig.2.20). The main Advantages of the MSE150 spindle are[44]:

- Increased productivity due to higher spindle speed up to 30,000 r.p.m.
- Better yarn qualities due to controlled vibration and uniform speeds from spindle position to position (speed difference<1%), and reduced vibrations
- Optimized process due to an infinitely variable, frequency controlled driving system
- Higher efficiency due to essentially less yarn breaks
- Reduced operating costs due to less maintenance
- Lower noise emission due to the lack of tangential belts and belt guiding elements
- Longer life of the spindle due to lower vibration level controlled temperature of the motor and the bearings due to an integrated cooling system.

Three-phase asynchronous motors, with 3 x 250 Volt max are being used as driving systems having rugged and solid construction. It is particularly suitable for the special requirements of round the clock operation in mills. TEMCO's new spindle conception of the individual motor drive is already being used in the latest generation of covering machines.

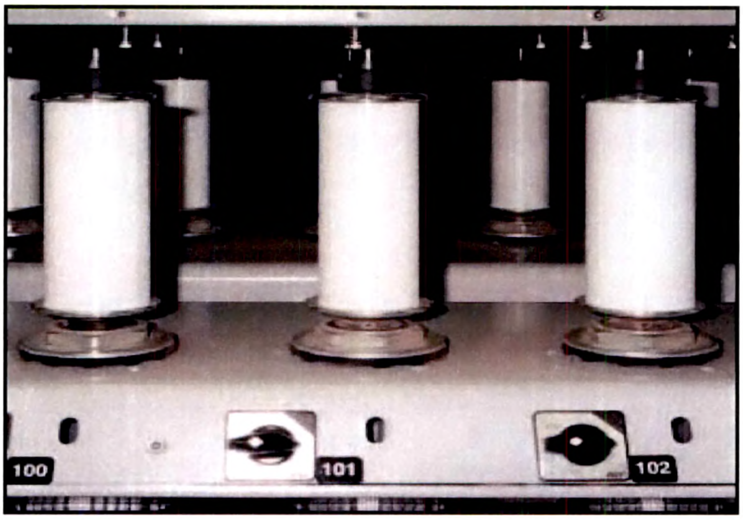



Fig. 2.20 Hollow spindles machine for the cover spinning process: MSE150

The electric power supply and control of the motor on spindles is made by means of frequency converters, which have been wired in a synchronous way with the feed rollers and take-up system. This means that the ramp-up time and ramp-down time of the machine is coordinated with the spindle and is controlled centrally, TEMCO motor spindle, MSE 150, for cover spinning process consists of integrated bearing, a synchronous motor, bobbin, as option and bobbin fixing system (Fig.2.21). The ramp-up and brake times are infinitely variably controlled. The braking period can be adjusted time wise by means of a regenerative brake. Each spindle individually can be manually started or stopped.

Fig. 2.21Spindle assemblies showing individual drive and integrated bearing

A special feature of the individual motor drive system is the striking reduction in noise level by almost 6 dB (A), which improves working conditions for the operating personal, in compliance with strict noise level pollution laws being enforced in the various countries. The reduction of noise comes from the elimination of the tangential belt as well as heavy bearing elements to guide the belt.

The integrated bearing assembly as shown in Fig. 2.21 is offering the advantages of more rigidity and higher dynamic load rating, both of which are prerequisites for the high speeds of operation up to 30,000 r.p.m. The bearing assembly is protected against dirt; thread laps and fluff by means of a double lip gasket and a rotating disc. These bearing have the facility of relubrication for longer life. The damping systems between the bearing and the housing as well as between the adapter and the spindle rail have been especially designed by TEMCO to reduce the vibrations and the bearing forces, by which the life of the spindle bearing assemblies is increased clearly and noticeably. This effect too, is contributing to the reduction of the noise level. Safe fastening of the bobbins and an ergonomic optimization are guaranteed by the newly developed one hand adaptor system. This allows easy change of bobbin during refilling.

## 2.9 QUALITY EVALUATION OF COMMINGLED YARN

The commingling process forms the nips along the yarn during the yarn passage through the nozzle. The nip frequency, nip regularity and nip stability are the important characteristics for the quality assessment of the yarn. The schematic representation of these is shown in model structure of commingled yarn given in Fig. 2.22.

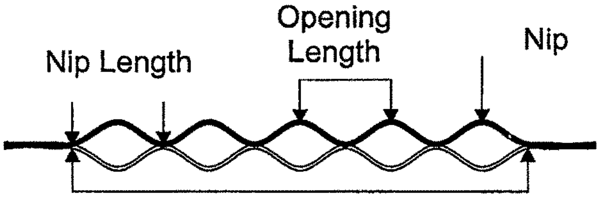



Fig. 2.22 Model Structure of commingled yarn

### 2.9.1 Nip Frequency and Nip Regularity

Nip frequency is, generally, expressed as number of nips per meter. The distance between two adjacent nips is called an "Opening length". Nip regularity is evaluated with the help of "Opening length" distribution. The determination of these parameters is accomplished by four different methods.

***a) Visual counting***

In this method[45], the commingled yarn is placed on the surface of water and the tangle lacing points so visualized that due to springing apart of filaments in open portion, they are counted manually. The distance between two nip points can also be measured. For better viewing and measurement, coloured water is used and a scale is fixed at the bottom of the water tray. The other alternative for clear visualization of nips is the electrostatic high voltage field; the filaments of the running thread spray out in those sections that are not interlaced. The interlaced structure becomes optically visible.

***d) Needle insertion***

This technique is commonly used and a number of commercial instruments are available. In principle, a needle is pushed through the yarn and moved backwards and forwards along the yarn until it is stopped by the presence of nips. Alternatively the yarn may be moved around a stationary penetrating needle. The length of open places and the frequency of nips may be recorded. The disadvantages of this method include the possibility of missing open places, when the nip frequency is high and failure of needle penetration, especially while evaluating low twisted yarns are tested.

***c) Thickness measurement***

Kanebo tester uses this principle, in which the commingled or interlaced yarns are scanned mechanically by means of a spring load situated in a measuring slot depending on yarn thickness. The other equipment, Reutlingen Interlace Counter, also measures nips through the yarn thickness measurement.

***d) Optical scanning***

This technique has been developed at Loughborough University of Technology. In this method, the yarn is moved at a steady speed in front of a

SLR camera so that a shadow of the yarn is focused onto the focal plane of the camera, where the line sensor is fixed at right angles to the yarn axis. As the yarn moves forward, the sensor scans the shadow and builds up an image representing thickness changes along the yarn. The data are then analysed to determine the yarn characteristics.

All these techniques have one or more drawbacks such as lack of standard, ineffectiveness, uneconomical costs, etc. However, the optical method seems to be more promising if it would be made economical with the help advanced of microcomputer technology. Sometimes the other parameters such as maximum opening length, interlacing intensity, etc. are also used for qualitative evaluation of commingled yarns. The interlacing intensity is an average thickness of the yarn. As the interlacing becomes more intense, an average yarn thickness increases.

***e) RICa Interlace Counter***

The RICa interlace counter as shown in Fig. 2.23 determines the number of nodes per unit length of yarn, the average yarn thickness, thickness of uninterlaced yarn, average node thickness, yarn compaction factor, node compaction factor, tack effectiveness and entanglement stability. The other standard values such as average length of the tack and CV% also can be evaluated[46].


Fig.2.23 Interlacing counter RICa

The continuous scanning of the yarn allows the destination of all the important tangle characteristics. This is helpful in designing new interlace jets, new yarns and for quality control in production. The measured and evaluated yarn characteristics are:

- Number of interlaces per meter
- Number of non-tangled places per meter
- Mean knot length
- Maximum knot length
- Mean knot thickness
- Mean open length
- Maximum open length
- Yarn thickness of tangled yarn
- Yarn thickness of non-tangled yarn
- Yarn compacting factor
- Knot compacting factor
- Tack effectiveness
- Analogue signal of yarn thickness over total test length
- Entanglement stability

The entanglement stability is determined with the other characteristics in only one test run. The CV values and frequency distributions for knot length and open length are additionally displayed.

The measured signal can be displayed on the screen in different scales. The program recommends a threshold value. The determined test conditions can be automatically adjusted. During the testing the tangled yarns are subjected to a most comprehensive analysis. Slightest differences are positively identified by statistical method.

### 2.9.2 Nip Stability

A further important feature of commingling process is nip stability. Warp yarns, which are going to be processed on loom without sizing, require a high level of nip stability. The yarns showing a high nip frequency and nip regularity may not perform properly on weaving machine.

Thus pertaining to nip strength measurement of commingled yarns, Weindorfer[32] has described the method of mechanical stressing to remove a few stable interlaces from the yarn. The index for interlaces is measured after and before mechanical stressing respectively. The other method, suggested by Clocan[52] *et. al.* is based on the measurement of maximum value of load tension upto, which the specific variation of the number of loops (open portions of the yarn) does not change after loading (ie. it is zero). They have, further, explained the effect of air pressure, yarn speed, number of filaments, cross-sectional shape of the filament and diameter of jet orifice on the stability of interlocking.

### 2.9.3 Blend Homogeneity

Mingling process offers the best possible means of blending continuous filaments. Blends of hybrid yarns like, glass/polypropylene, carbon/polyester, glass/polypropylene, glass/nylon etc. offer interesting possibilities for producing yarn for composite applications. In order to achieve high degree of blend uniformity of mingled yarns, it is essential to study the influence of process, material and nozzle parameters on blend homogeneity.

Many research workers have described the techniques of determining the blend uniformity in staple fibre yarn. They studied mixing and migrating behaviour of filament in hybrid yarn studied by visual inspection of SEM. Coplan has developed statistical techniques of characterizing quantitatively the blend homogeneity in any yarn. Some of the researchers have developed the image analysis technique to find the distribution of each yarn component in blend yarn.

***a) SEM Analysis***

The Scanning Electron Microscope provides a different approach to the direct examination of surfaces and distribution of component in cross sectional area[49]. Electron lenses are used in the illuminating system to form a greatly reduced image of an electron source and this very small electron probe, about 100Å in diameter, is scanned across the specimen by electrostatic deflecting electrodes, as in a television system. Secondary electrons leaving the specimen are collected directly into an electron multiplier and, after amplification; the signal is used to modulate the beam intensity of cathode ray tube. At the same time, the beam scans the screen of the tube in a raster in synchronization with the scanning spot in the microscope. Contrast in this image will depend on the secondary electron characteristics of the surface, which in turn will depend on the local angle of incidence of the primary electron probe. The schematic diagram of Scanning Electron Microscope is shown in Fig 2.24.

E. Klata et.al.[50] has analysed SEM of hybrid yarns produced by three different spinning systems viz. friction spinning, ring twisting and air texturing. Each of these systems gives a different structure of the yarn and a different level of blending of the reinforcing and thermoplastic fibres Fig. 2.25. They stallization and melting behaviour of PA 6 in the yarns and the composites were studied by differential scanning calorimeter. The different structure of the hybrid yarns lead to differences in the crystallinity of PA 6 in the yarns and the composites. The mechanical properties of the thermoplastic yarns and the composites are influenced, among other factors, by the crystal structure of the polymer.

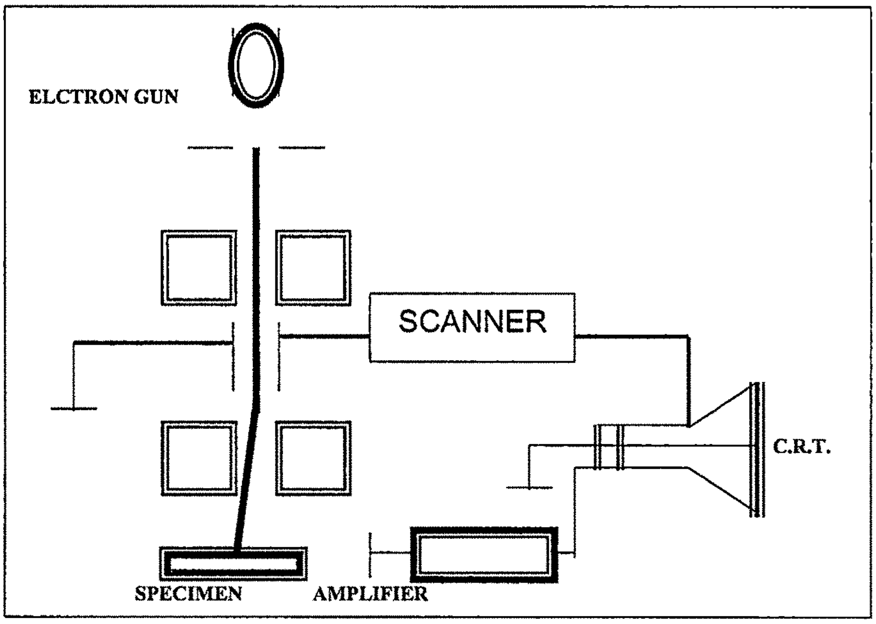
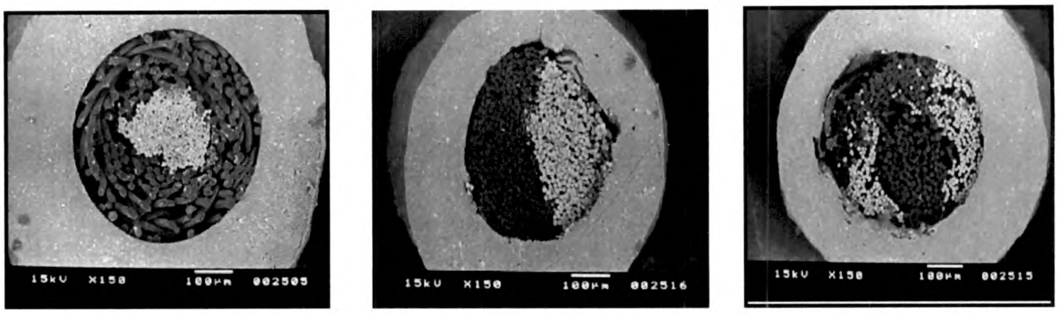
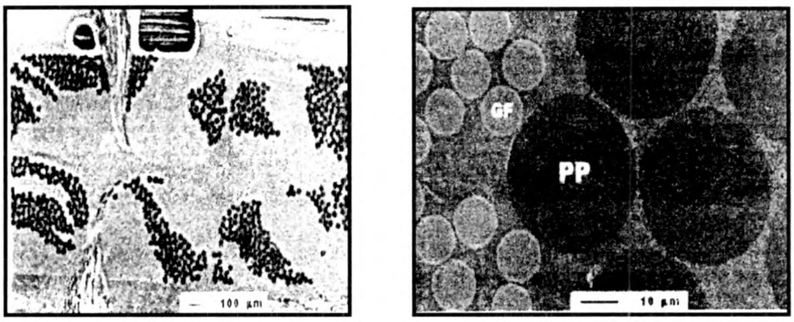



Fig. 2.24 The Scanning Electron Microscope

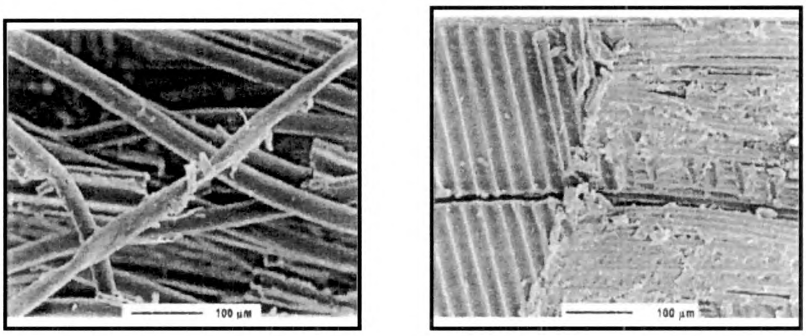



(a) Friction spun yarn (b) Twisted yarn (c) Air textured yarn

Fig. 2.25 The SEM of various hybrid yarns




a) Glass/Polypropylene Distribution in hybrid composite




b) Glass/ Polypropylene Impacted fracture Surface

Fig 2.26 SEM of Glass/ Polypropylene hybrid composite

C. Thanomsilp[51] has investigated SEM of the cross sections of laminates in order to view the distribution of thermoplastic fibres and glass fibres within the hybrid composite. The SEM micrographs of all hybrid yarn composites shows random distribution of glass fibre and thermoplastic with all most side-by-side arrangement(Fig. 2.26(a)). The effect of curing temperature, impacted fracture surface are also studied (Fig. 2.26(b))

***d) Image analysis***

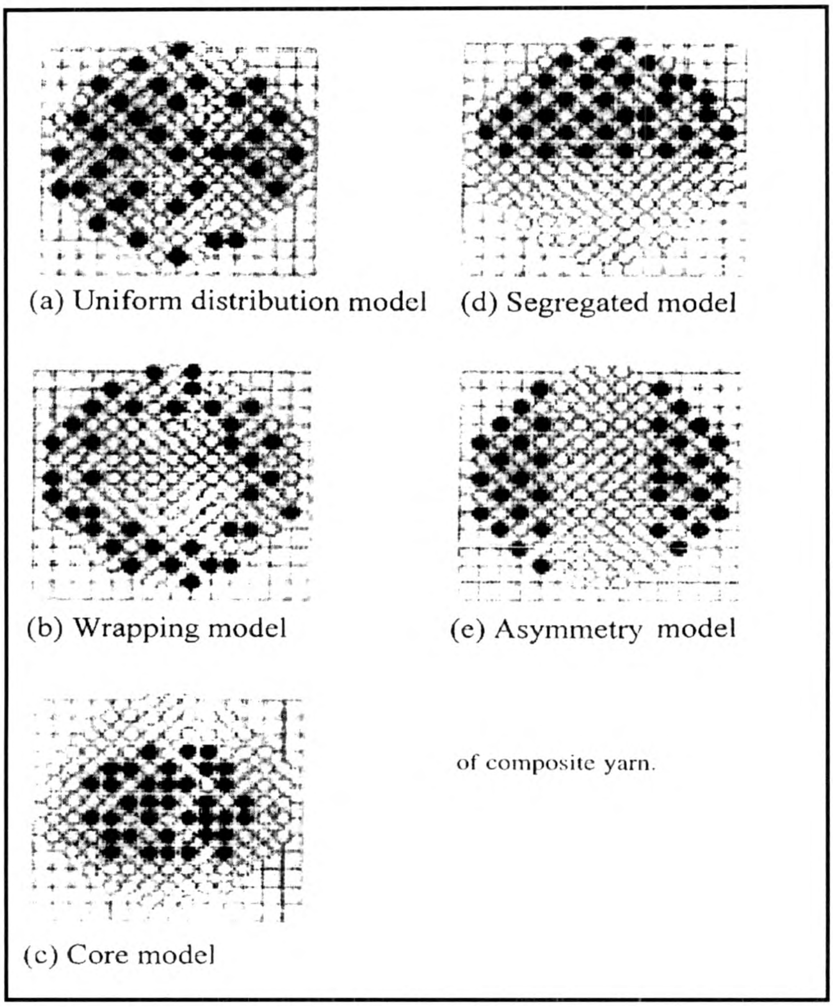



Fig. 2.27 various models representing filament distribution in composite yarn

Ching-Iuan Su[52] has discussed the application of computer image analysis to study the cross section of composite yarn. It attempted to quantify the distribution of dispersed filament in image of cross section obtained with SEM and analyzed by computer algorithms. This work also defined parameters such as radial and lateral distribution. The model uses for these studies are shown in Fig. 2.27.

## 2.10 APPLICATIONS OF HYBRID YARN

The hybrid yarns are generally used as reinforced component for making thermoplastic composites. The advantages of thermoplastic composites over thermoset composites have already been discussed. Thereby there is a

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growing interest in applications of thermoplastic composites in areas much wider than earlier and these include sports and automotive applications.

Thermoplastic materials are used in various industrial applications listed in Table 2.3 including aerospace, automotive, defense, construction, rail, sports, medical, oil/gas energy and irrigation (Fig.2.28). The thermoplastic composites offer many advantages over traditional steel, thermoset composites, and injection moulded automotive parts owing to lighter mass and flexible structural designs. Historically, the cost to replace these traditional materials with thermoplastic composite materials has limited the use of advanced materials, primarily due to tooling costs and throughputs per capital machine investment. Compared to thermosets, thermoplastic materials offer zero solvent emissions reduced material scrap, improved work safety conditions, elimination of painting process steps, elimination of tedious production steps due to automation and finally greatly improved recyclability of the polymer.

The main drivers for the automotive applications are cost reduction, weight reduction and recyclability. The cost of composite moulded parts is becoming increasingly competitive for applications such as bumper beams, load floors, under-body shields etc.The thermoplastic composites are also used in number of applications in the various industrial applications, which can afford to use a high premium product with a long life cycle. The important end uses of thermoplastic composites in aircraft applications are in access panels and doors, engine cowlings, movable wing surfaces such as elevators, rudders and spoilers. Aircraft floor panels are made through thermo folding wherein the laminate is locally heated and folded. This process gives durable products at low cost for such applications. Mouriz et.al.[53] in their review has listed the following examples in a variety of demonstration structures for aircraft (Fig. 2.29 (a)).

Aerospace demonstrator components made with 3D woven composites

- Turbine engine thrust reversers, rotors, blades, insulation, structural reinforcement and heat exchangers

- Rocket motors, nozzles and fastners
- Engine mounts
- T-section elements for primary fuselage frame structures
- Rib, cross-blade and multi-blade stiffened panels
- Leading edges to wings

Table 2.3Applications of Thermoplastic Composites

| Sr. No | Sector | Applications |
|---|---|---|
| 1 | Building & Construction | Window frames & components, Cladding – exterior horizontal & vertical, Door frames & components, Ducting, Roofline products, Shingles roof tiles etc. |
| 2 | Interiors/Internal finishes | Interior panels, Decorative profiles, Office furniture, Kitchen cabinets, Shelving, Worktops, Blinds shutters, Skirting boards, railings etc. |
| 3 | Automotive | Door & head liners, Ducting, Interior panels, Rear Shelves, Spare tyre covers, Truck floors etc. |
| 4 | Garden & Outdoor | Decking, Fencing & fence posts, Garden furniture, Shelters & sheds, Park benches, Playground equipment, Play ground surfaces etc. |
| 5 | Industrial/ Infrastructure | Industrial flooring, Railings, Marine pilings/bulkheads, Railway sleepers etc. |
| 6 | Aircraft | Turbine engine thrust reversers, Rotors, blades, Insulation, Structural reinforcement and Heat exchangers, Rocket motors, Nozzles and Fasteners. |

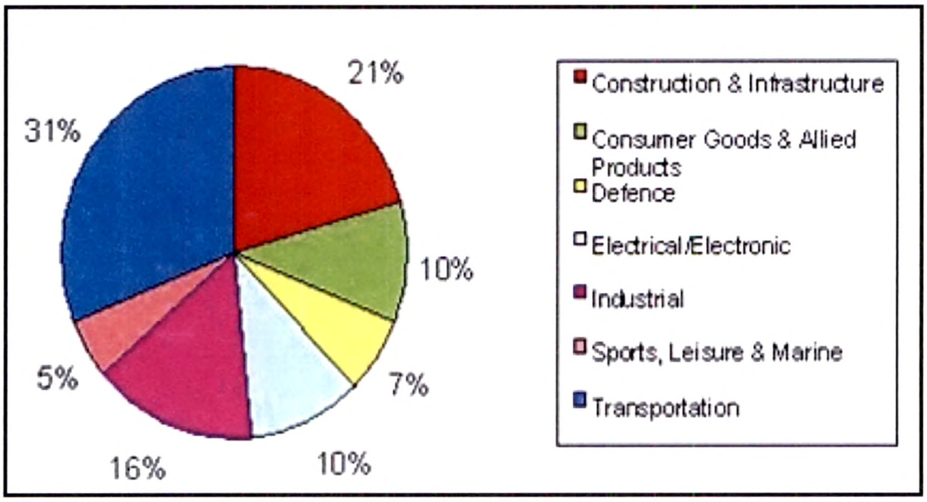



Fig 2.28 Various applications of thermoplastic composite

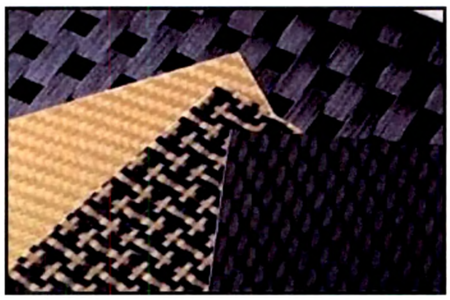
a) Aircraft structure

b) Wind turbine blade

c) Wind mill

d) Door-post

e) Overhead panel



f) Preforms

Fig 2.29 Applications of thermoplastic composites

The other applications viz. wind turbine blade, wind mill, door-post, overhead panel (Fig. 2.29(b)- Fig. 2.29 (e)), where three-dimensional woven composites have been used to improve the strength of repairs to damaged hulls. 3D braided composites can be used in beams and shells for automobile bodies and chassis, as well as for drive shafts. 3D knitted sandwich composites can be used in bicycle helmet mould rather than prepreg tape or 2D woven fabric. Furthermore, the knit architecture of the skin can be controlled to provide optimum airflow for heat dissipation from the wearer's head, which is a major benefit during endurance cycling. It has been reported that composites reinforced with non-crimp multi-axial glass fabrics were being considered for use in car bumper bars, floor panels and door members.

Composites have been used in the rail industry for many years in such applications such as seating, walls, ceiling, platform floors, interior doors, window panels, side frames, front structures, etc. The general driving forces for polymer matrix composites in transportation includes cost reduction, reduced weight, excellent mechanical properties, durability, noise/vibration dampening, aesthetics, dent resistance, corrosion resistance and dimensional stability. For example, Honeycomb composite structures offer excellent energy absorption, and are used in the front structure of the TGV trains to absorb around 2MJ energy. So far, thermoplastics have not been used in rail applications as widely as in automotive and aerospace applications. But considerable market growth is expected in this area.

### 2.10.1 Conductive Textiles

In recent years, a new area of research has emerged on textile based conductive materials called "Conductive Textiles". The field of conductive textiles can be viewed as an integration of technologies of materials, electronics and textiles in order to create a new generation of flexible and comfortable multifunctional textile structures with conductive characteristics. These structures can be made from specially made hybrid yarns with one of the components having conductive characteristics. These yarns are used for for manufacture of conductive textiles for various applications of fabrics and laminates. The conductive textiles find their applications in telephone instruments, computer enclosures, medical devices, electronic monitors, navigation equipment, laser calibration equipment, oscilloscope housings, packaging, grounding, conductive gaskets, bonding straps, cables, connectors, screens etc.

### 2.10.2 Methods of Imparting Electrical Properties at Fibre Stage

The conductive characteristics can be imparted to textile materials at any of the intermediate stages i.e fibre, yarn or fabric. The various methods of imparting the required electrical properties at fibre, yarn or fabric stage[55] are as follows.

#### *a) Draw blending of Metal and Textile Slivers*

Relatively high conductivity $10^5$ $[\text{ohm.cm}]^{-1}$ can be obtained by draw blending of metal fibre sliver with slivers composed of conventional textile fibres. The process is difficult as metal fibres are as much as five times heavier than most textile fibres. Moreover the metallic fibres are brittle and can abrade the spinning equipments. These hybrid yarns produce the fabric with metallised hand. K. B. Cheng *et. al.*[62] had used this method in which stainless steel and polyester staple fibres were used at the drawing stage.

#### *b) Treatment with Metallic Salts*

Copper sulphide and copper iodide are the two predominant metallic salts used to coat the fibres. But this method gives yarn with low conductivity. This is primarily used in carpet industry, where antistatic performance is required. Generally the yarns with conductivities ranging from $10^{-6}$ to $10^{-1}$ $[\text{ohm.cm}]^{-1}$ can be achieved depending on the chemicals and the process used. Varieties of fibres have been used, including nylon, polyester, wool and acrylic.

#### *c) Galvanic Coating*

Yarn with high conductivity>$10^4$ $[\text{ohm.cm}]^{-1}$ can be obtained by Galvanic coating. This method, must be applied to a conductive substance, hence it is limited to carbon and graphite fibres. As the galvanic coating is difficult and expensive process it is rarely used in textile industry.

***d) Coating fibres with Conductive particles suspended in a Resin***

In this method, fibres can be coated with a resin in which a high concentration of conductive particles has been dispersed. Some of the earliest conductive products were made by applying high concentration of carbon containing resin to a fibre. Carbon fibres have fairly high conductivity, especially if pure carbon is used. Unfortunately, carbon can be difficult to process and any significant amount of carbon will impart a black colour to the end product.

Acrylic and Nylon fibres have been coated with a rubbery adhesive containing dispersed silver. Nylon is believed to be the best fibre to coat with particles dispersed in an adhesive because it has a surface containing small cavities that serve as chelating points.

***e) Vacuum Spraying***

Vacuum spraying is a relatively inexpensive method that produces metal coated fibres with conductivities as high as $10^4$ $[ohm.cm]^{-1}$. But this method has certain limitations such as unstable construction and low adhesion between metal and fibre. The lack of adhesion and the limited thickness of coating make it difficult to achieve high conductivity. More over fibre also shows lower resistance to corrosion and wear. The process is comparatively difficult. This method can also be used to coat fabrics with a metal.Other methods for making fibres conductive can also be used to treat yarns and fabrics.

**2.10.3 Methods Of Imparting Electrical Properties At Yarn Stage**

Normally spun yarns are made on any of the conventional or new spinning systems. Various types of speciality yarns are also made on the existing spinning machines. The speciality yarn with core-sheath bicomponent yarns are prepared to impart electrical properties to the yarns. The core yarns can be manufactured by various spinning methods like ring spinning, rotor spinning, air jet spinning and friction spinning by the incorporation of certain attachments to conventional spinning system.

### *a) Ring spinning*

K.B.Cheng *et.al.*[60,62] had produced core-sheath type composite yarns on Ring spinning system. Thin metal wire was used as core and cotton fibre was used as sheath. The schematic view of feeding of core and drafted staple fibre sheath into yarn is shown in Fig. 2.30.The yarn formation is achived by conventional Ring-traveller method of twist insertion.

### *b) Open end spinning*

The another method, in which the metal wire is incorporated in the yarn as a core and wrapped by staple fibres by means of Rotor is known as Rotor spinning. As shown in Fig. 2.31, the core filament passing through rotor center is surrounded by spiral ring of fibres formed by the Rotor. This technique can also be used to produce conductive yarn with fibre cover. However, another open-end spinning method viz. friction spinning is widely used as compared to rotor spinning[54]

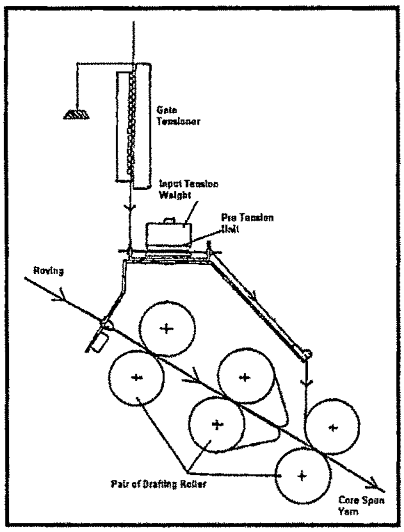



Fig. 2.30 Ring spinning

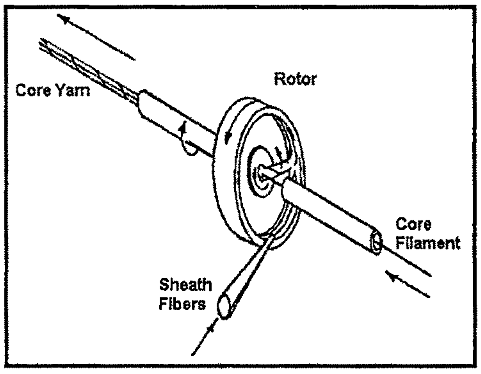
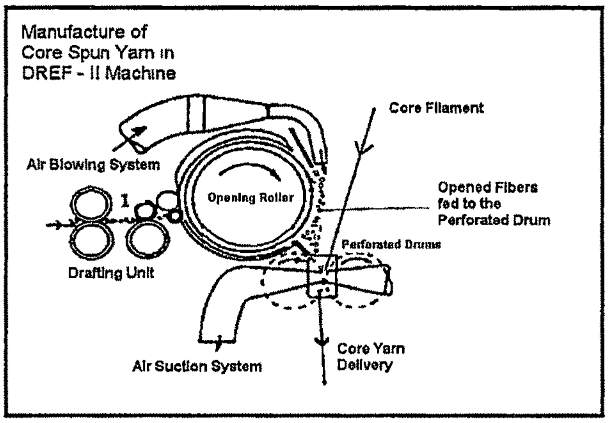


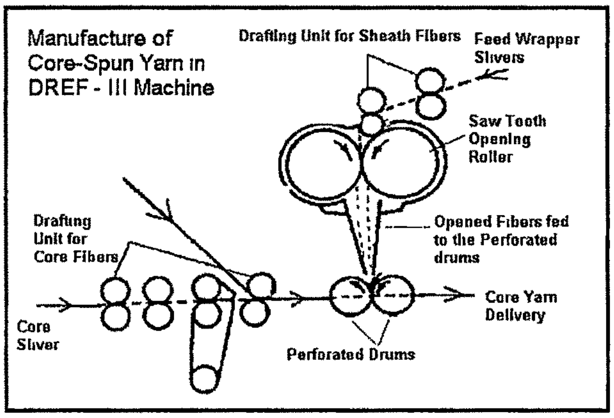

Fig. 2.31 Open end spinning

### *c) Friction spinning*

The speciality hybrid yarn can also prepared on newly developed friction. As shown in Fig. 2.32 metal wires can be incorporated as core component directly between perforated drums in case of Dref II or in the front roller nip of drafting system in case of Dref III machine.




(a) Dref-II




(b) Dref-III

Fig. 2.32 Various frictional spinning systems.

Studies performed at SITRA on the various types of hybrid yarns prepared on Dref-III machine incorporating copper wire in the core, wrapped by cotton, polyester and polypropylene fibres show good results pertaining to characteristics of these conductive yarns.

***d) Wrap spinning (Cover spinning)***

Wrapping a mono or multi filament around a twisted or a twistless fibreous core produces a wrapped yarn with combination of's' or 'z' warp. Also, yarn wrapped with both 's' and 'z' twist directions called as 'x' configuration, which was reported to give higher strength and elongation as compared to that of only 's' or 'z' wrapped yarns. Hsin-Chuan Chen et. al[59] had used this wrapping method in terms of rotor twister or rotor wrapping twister or hollow spindle machine to form conductive yarns.

***e) Production of yarn from Bi-component fibres***

Bi-component fibres can be wet, dry or melt spun. It is important that the two component polymers have adequate surface bonding and that the viscosities of both solutions and melts are compatible. The different polymers are combine at the point of extrusion through the spinneret. Fig. 2.33 shows the principle of the technology for forming the basic side-by-side and sheath-core bi-component fibres. To maintain uniformity throughout the length of the filament pumping pressures must remain constant and the flow of liquids must be non-turbulent. By altering the spinneret configurations, a variety of other cross sectional forms can be produced. Some variations of circular cross-section side-by-side and sheath core bi-component fibres are shown in Fig. 2.34.

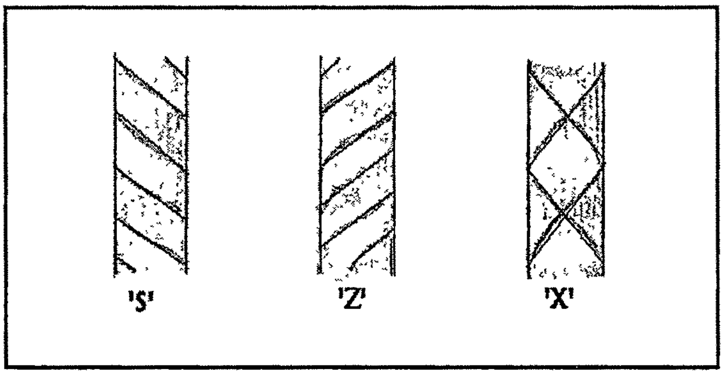



Fig. 2.33 Different types of wrap yarns

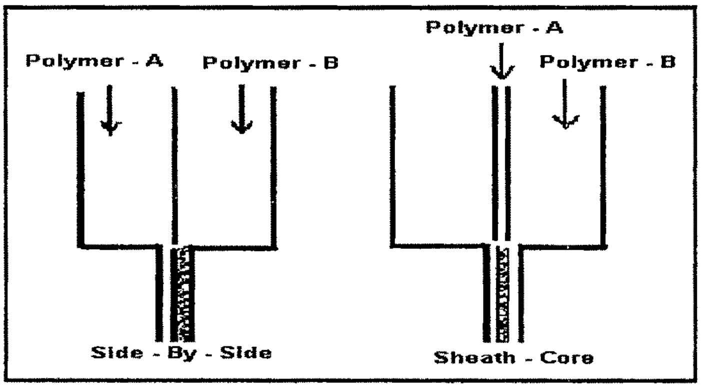



Fig. 2.34 Side-by -Side and Sheath-Core yarn



Hireni Mankodi
M S University of Baroda

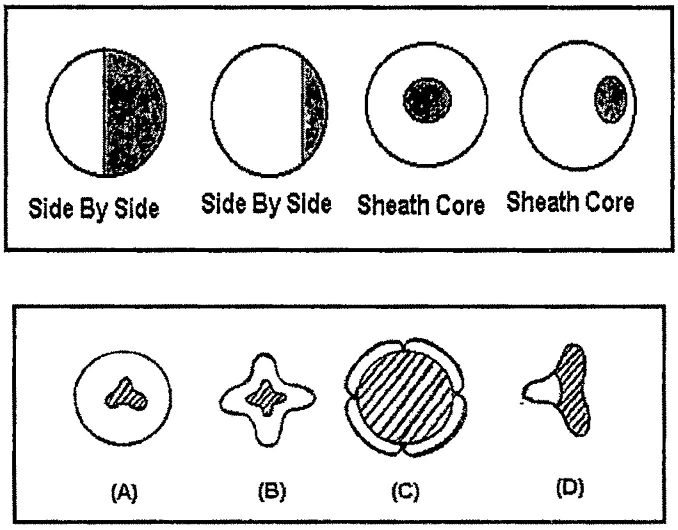



Fig. 2.35 Variation in cross section of bicomponent yarns

Also, more complex cross sectional configurations of bi-component fibre can be obtained by using shaped, non-circular orifices in the spinneret ie. (A),(B) and (C) configuration for a sheath core bi-component fibre and (D) side-by-side type as shown in Fig. 2.35

An electrically conductive bi-component filament yarn was also produced by melt spinning, where the sheath included an electrically conductive fine power of carbon black and the core was a synthetic polymer. Stainless steel was used as conductive filler to produce the hybrid yarn[60].More recently, various metal oxides have been incorporated into the sheath of a bi-component yarn. Unlike, carbon, metal oxides are often colourless and can be doped to increase conductivity. Other methods of producing an electrically conductive bi-component material include those using a high concentration of a metal compound in the core of the yarn.

***f) Speciality yarns***

The special yarn structures are also made using various post spinning processes. Braiding, plying, cabling etc. by the diagonal interlacing of yarns, is one of the oldest methods for producing fabrics and cords. Flexible braided cord yarn can be made electrically conductive simply by substituting one or more of its component yarns by fine metal wire or a yarn treated with an electrically conductive material. Single yarns can be twisted together to form plied yarns, which can be further twisted together to form cabled yarns. In case of braiding, during manufacture, there is the opportunity to substitute a conventional yarn by electrically conductive yarns.

Novelty yarns are generally used for decorative, rather than functional purposes. However, some novelty yarn constructions offer opportunities for replacement of conventional yarn components by one that conduct electricity.

### 2.10.4 Imparting Electrical Properties at Fabric Stage

The fabric surface can be laminated by conductive layers by various method such as coating of conductive material, zinc spraying, ionic plating, vacuum metallized sputtering and metal foil binding viz. by any of the followings:

- Adding conductive fillers such as conductive carbon black, carbon fibres, metallized fibres, metal fibres (stainless steel, aluminum, copper), and metal powders and flakes (Al, Cu, Ag, Ni) to the insulating material.
- Incorporating conductive fibres or yarns into the fabric; because the fibres are closely spaced, conductive paths can be easily established. Hsin-Chuan Chen *et. al.*[58,59] had used this method to produce conductive fabrics.
- Coating the surface of the fabrics by various methods like electro plating, sputtering, evaporative deposition, conventional coating technique (direct coating) and coating with conductive polymers.

## 2.11 ELECTRICAL PROPERTIES OF CONDUCTIVE MATERIAL

In recent years, due to the progress of science and technology, numbers of electrical and electronic devices have been developed for various applications. There is a huge demand for materials having conductive or semi-conductive characteristics to fulfill certain requirements such as accuracy, speed, compactness and protection of electronic equipments. The design and development of functional conductive materials is major aspect for researchers and manufacturers. The performance of insulating material improves when it incorporates conductive material to be used for various applications like antistatic material, electrostatic material and electromagnetic material. The performance of this product depends on electrical properties viz. dielectric strength, surface resistivity, volume resistivity, electrostatic discharge and shielding effectiveness. The basic principle, theories and measurement techniques of these properties are explained in this section.

### 2.11.1 Dielectric Strength and Its Measurement

The dielectric strength of an insulating material is defined as the maximum voltage required to break the product at dielectric breakdown[68]. Dielectric strength is expressed in volts per unit of thickness. All insulators allow a small amount of current to leak through and around them. Only the perfect insulator, can be completely free from the current leakage. Even the small leakage generates heat, providing an easier access to more current. The process slowly accelerates with time and the amount of voltage applied until a failure in terms of dielectric breakdown occurs. Dielectric strength, which indicates electrical strength of the material as an insulator, is very important characteristic of an insulating material. Higher the dielectric strength better would be the quality of insulator.

A variable transformer and a pair of electrodes are used in the basic set up for a dielectric strength test. Specimens of any desirable thickness prepared from the material to be tested can be used. However specimen thickness commonly used as 1/16 inch. The dielectric strength (KV/mm) of an insulating material is calculated as:

Dielectric strength (KV/ mm) = Breakdown Voltage (V) / Thickness (mm)

Three basic procedures have been developed to determine dielectric strength of an insulator.

a) Short time method

In this method, the voltage is increased from zero to breakdown voltage at uniform rate. The rate of rise is generally 100, 500, 1000, or 3000 V/sec until the failure occurs. The failure is made evident by actual rupture or decomposition of the specimen. Sometimes a circuit breaker or other similar devices are employed to signal the voltage breakdown.

b) Slow rate of rise method

In this method, the test is carried out by applying the initial voltage approximately equal to 50 percent of the breakdown voltage. After this, the voltage is increased at a uniform rate until the breakdown occurs.

c) Step by step method

The step by step test method requires applying initial voltage equal to 50 percent of the breakdown voltage as determined by the short time test and then increasing the voltage in equal increments and held for specified time periods, until the specimen breaks down. The factors affecting the test results are specimen thickness, temperature, humidity electrodes, time, mechanical stress and processing.

**2.11.2 Surface Resistivity and Its Measurment**

Surface Resistivity is a measure of the electrical resistance for unit area of material and is the primary criterion for classifying sheets, films, fabrics, foils, and coatings as low, moderately, or highly insulating.

Surface resistivity can be measured in accordance with ASTM D257-93. The method involves placing a concentric cylindrical electrode cell onto a circular specimen of material (Fig. 2.36(a)). A voltage is applied to the cell and the current across the sample surface is measured. Surface resistivity is calculated using the known voltage, the measured current, and the geometrical relationship between the electrodes. The Fig. 2.36(b) shows the details of measurement of surface resistivity using Meohmeter.

The rate at which the charge on a material relaxes or decays provides another indication of its relative insulating or conductive character and serves as a useful companion to measurement of surface resistivity. Placing a speciment into an electrode assembly and charging the sample using a corona source, measures the charge relaxation rate. The electrode assembly is then grounded and the time required for the charge on the sample to relax to 1/e or

37 percent of its initial value is measured using a timer and an electrostatic field meter. Because of the effect of atmospheric and absorbed moisture on surface resistivity and charge relaxation rate, these tests are performed at ambient and low relative humidity conditions.

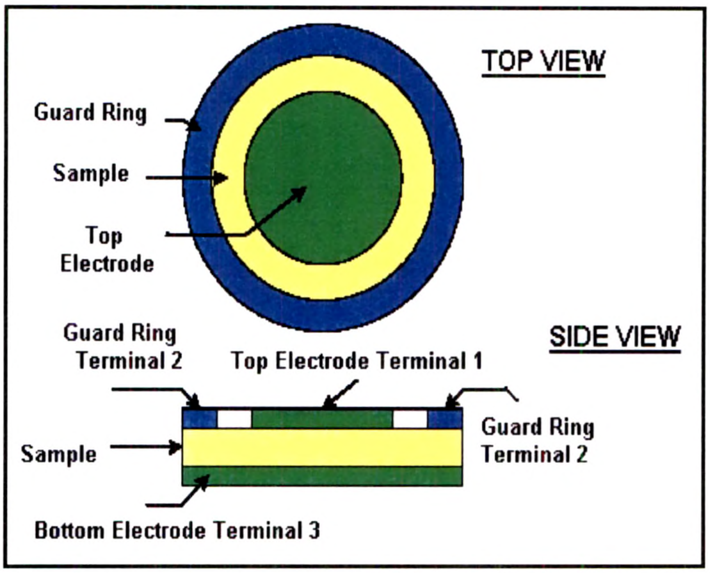



Fig 2.36 (a) ASTM D257 Test Cell

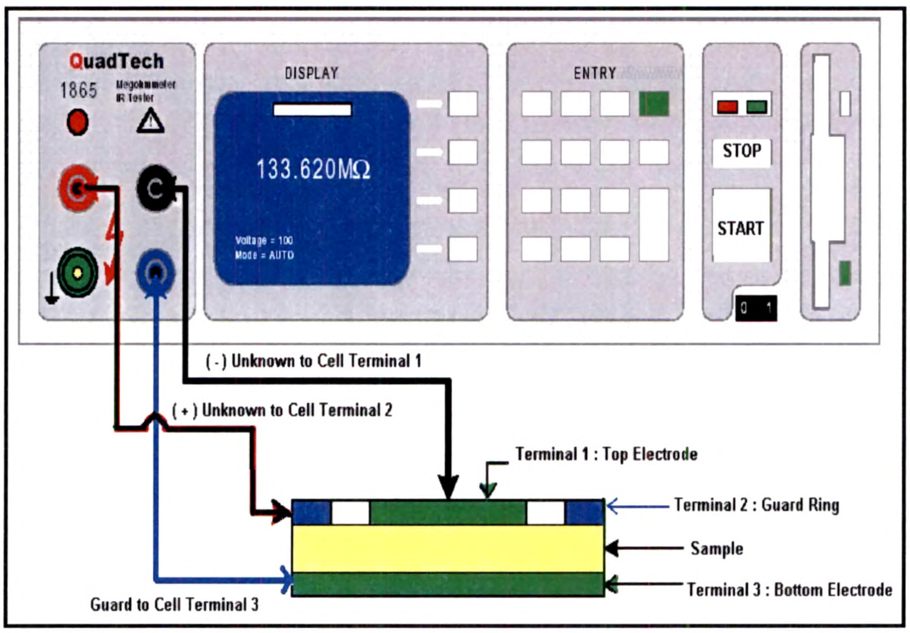



Fig. 2.36(b) Surface Resistivity Measurement using Meohmmeter



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### 2.11.3 Volume Resistivity and Its Measurement

Volume resistivity is a measure of the electrical resistance for unit volume of material. A material can be classified as insulating, antistatic or conductive base on its volume resistivity. Volume Resistivity for sheets, films, fabrics, foils, and coatings can be measured in accordance with ASTM D257-93. This involves placing a sample of the material between two electrodes of known geometry. A voltage is applied to one electrode, and the current passing through the material to the other electrode is measured. Volume Resistivity is calculated using the known voltage, the measured current, the measured thickness of the sample and the geometrical relationship between the electrodes. The rate at which the charge on a material relaxes or decays provides another indication of its relative insulating or conducting character and serves as a useful companion to measure of volume resistivity. The range of surface and volume resistively for different materials are given in Table 2.4.

Table 2.4 Range of Resistivity for Different Materials

| Material Type | Surface resistivity (W/sq) | Volume resistivity (W-cm) |
|---|---|---|
| Conductive | $<1 \times 10^5$ | $<1 \times 10^4$ |
| Dissipative | $1 \times 10^5$, $<1 \times 10^{12}$ | $1 \times 10^4$, $<1 \times 10^{11}$ |
| Electrostatic Shielding | $<1 \times 10^4$ | $<1 \times 10^3$ |
| Insulative | $1 \times 10^{12}$ | $1 \times 10^{11}$ |
| Antistatic | Not correlated | Not correlated |

## 2.12 MANUFACTURE OF THERMOPLASTIC COMPOSITES

### 2.12.1 Sheet Forming of Thermoplastic Composites

The process of sheet-formation for thermoplastic composites is much similar to that of sheet-formation in case of metals or plastics. A solid composite laminate is heated marginally above its melting temperature and rapidly formed over, or into, a complex-shaped mould. Fig. 2.37 shows a typical process, in which the composite sheet is heated rapidly in an infrared oven, and then indexed between two cool tools, which close rapidly to form and cool

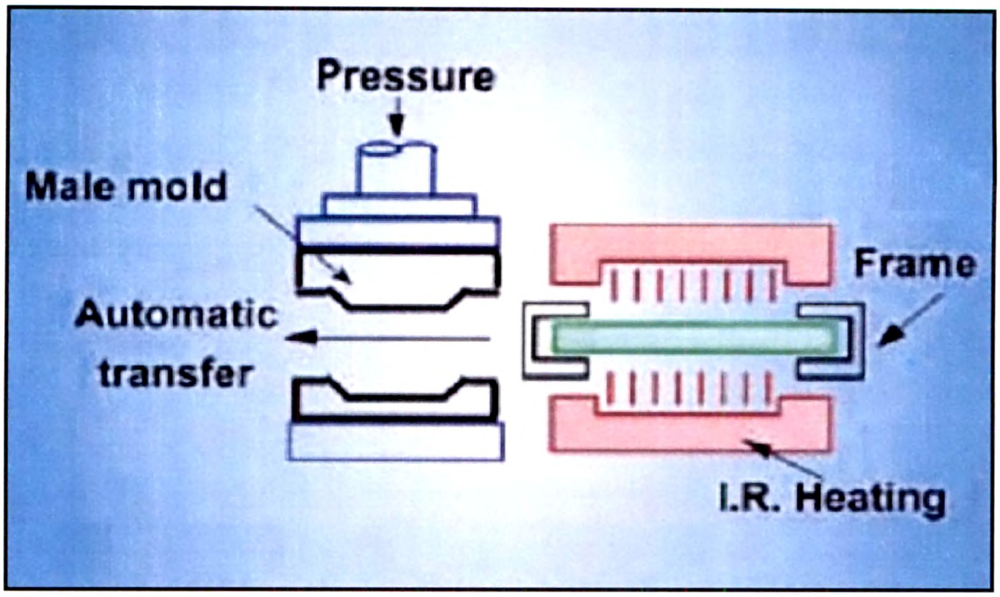


Fig. 2.37 Press-Forming of thermoplastic composite sheets

the sheet. The main advantage of this process is that very fast cycle times can be achieved, but it is limited to make the components with simple or medium shape complexity.

### 2.12.2 Tape-laying of Thermoplastic Composites

Thermoplastic composites, because of their chemistry, can be rapidly heated and rapidly cooled without any damaging effects to their microstructure. The tape-laying process uses this principle to locally heat and melt, consolidate, and cool a tape of thermoplastic prepreg, while placing it in position (Fig. 2.38).

Thermoset tape-placement has been developed for many years, with large, seven-axis robotically-controlled fibre-placement systems in operation in many aerospace plants worldwide. The difference between a thermoplastic and a thermoset system is the extra heating, consolidation and cooling equipment, needed with the head. The main advantage of the thermoplastic system is that the product is completely finished once the tape has been laid, whereas the thermoset product must be further bagged and cured in an autoclave.

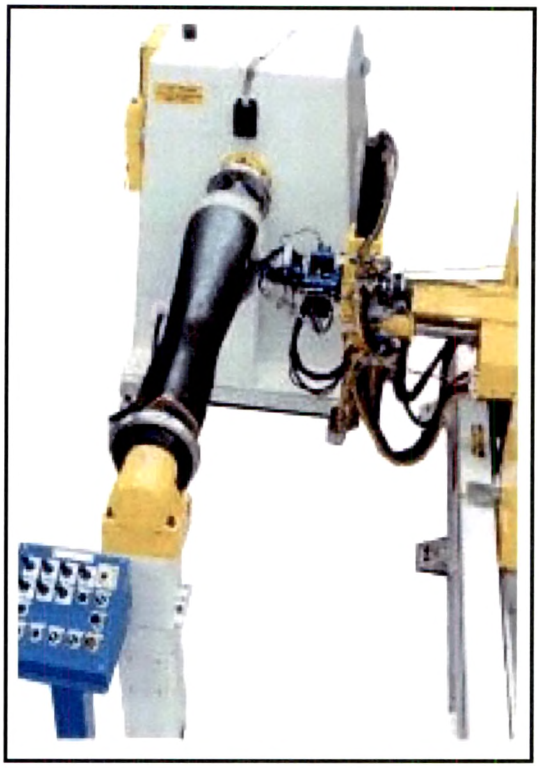

Fig. 2.38 Tape-laying of thermoplastic composites

### 2.12.3 Liquid Moulding

Advanced thermoset composites have traditionally been hand-laminated and cured under vacuum or in autoclaves. While suitable for low-volume applications in the aerospace sector, the recent trends have sought to use closed-mould processes such as liquid moulding, where the dry preform is laid either between two rigid tools or between one rigid and one soft tool or bag material. The liquid thermoset resin is then injected or infused through the reinforcement (Fig. 2.39). The main advantage of this process for aerospace is that the dimensional tolerances achieved are much better than with autoclaving process. The automation of the process improves the potential for other sectors such as those leading to higher volumes and faster cycle times. It also requires lower moulding pressures of about 1-5 bar, thus light, inexpensive tooling can be used. The process is currently limited to thermoset materials, and their cycle times are relatively long because of the necessity for chemical curing.

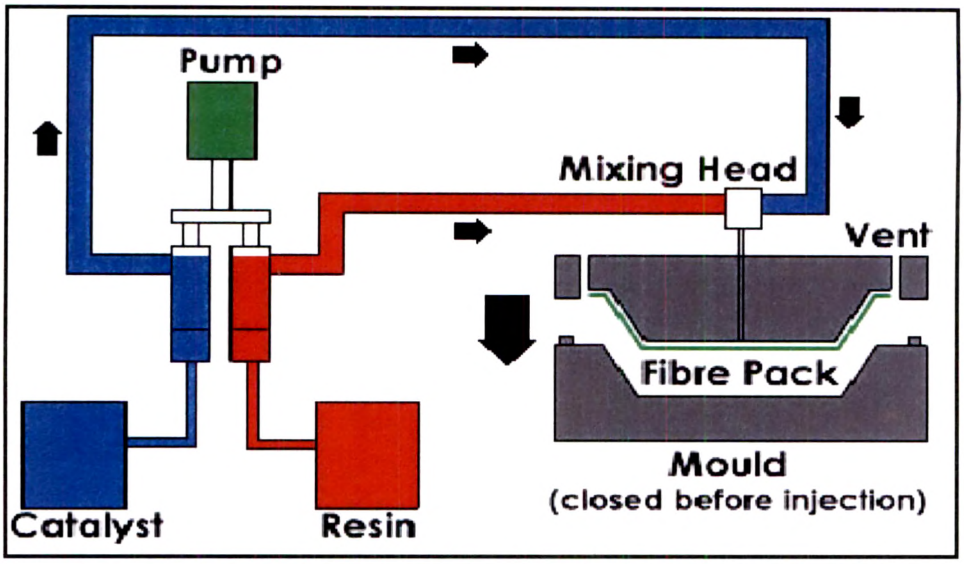


Fig. 2.39 Liquid Moulding of a Thermoset Resin

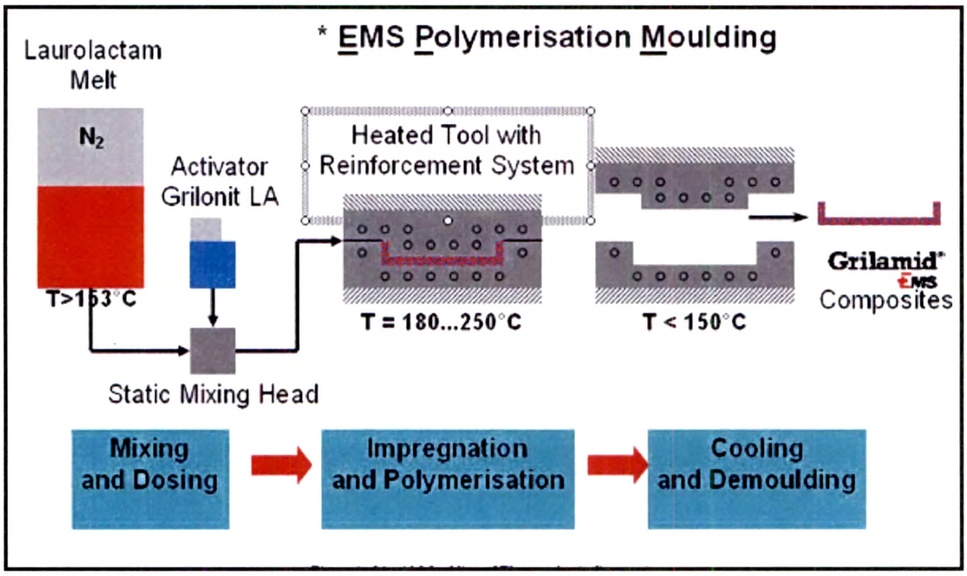


Fig. 2.40 Liquid-Moulding of Thermoplastic Composites

The new generations of thermoplastic materials are processed in a water-like state, and thus need much lower pressure, less expensive tooling, and lower energy input, while retaining all of the attractive properties of thermoplastic materials. Examples of the new liquid-moulded thermoplastic composites are Cyclics PBT from Cyclics Corp. (US) and Grilamid PA-12 materials from Ems-Chemie AG (Switzerland) and The end-of-life recycling can be easily achieved by chemical means, or by re-melting and to reuse as injection-moulding compounds.

The disadvantage of thermoplastic resins is that the melts have a high viscosity, typically above 500 Pa.s, which is too viscous to infiltrate high-volume fraction of fibres. Fig. 2.40 illustrates the principle of liquid moulding of thermoplastics. The low viscosity resins, now available are injected into the composite as an activated monomer, with a resulting low viscosity. Once infiltrated, polymerization takes place in-situ, yielding a semi-crystalline thermoplastic composite with all the inherent advantages of toughness, solvent resistance, dielectric strength and recyclability.